Auburn University

Effect of Strand Spacing on Development of Prestressing Strand

Prepared by

Thomas E. Cousins
J. Michael Stallings
Michael B. Simmons

Prepared for

Alaska Department of Transportation and Public Facilities
Juneau, Alaska

Highway Research Center
Harbert Engineering Center
Auburn University, Alabama 36849-5337

August 1993

EFFECT OF STRAND SPACING ON DEVELOPMENT OF PRESTRESSING STRAND

Prepared by

Thomas E. Cousins
J. Michael Stallings
Michael B. Simmons

Submitted to

Alaska Department of Transportation and Public Facilities
Juneau, Alaska

August 1993

ACKNOWLEDGEMENTS

The research reported in this paper was conducted at Auburn University with the support of the Alaska Department of Transportation and Public Facilities and the Auburn University Highway Research Center. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the agencies listed. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

1. INTRODUCTION

1.1 Overview

Over the years much research into the structural properties of prestressed concrete has been performed, but very little in the specific area of strand spacing requirements in pretensioned, prestressed concrete bridge girders. For about thirty years the American Concrete Institute (ACI) and the American Association of State Highway & Transportation Officials (AASHTO) have either required or recommended a minimum clear strand spacing of three strand diameters in pretensioned, prestressed concrete members (ACI 7.6.7.1, AASHTO 9.25.2.1) [1,2]. In addition AASHTO requires that the clear spacing be at least one-third larger than the largest aggregate size to allow for aggregate passage between prestressing strands (AASHTO 9.25.2.1) [2]; however, this requirement rarely controls strand spacing. Typically, these requirements translate into a center-to-center spacing of 2.0 inches for 0.5 inch diameter prestressing strand and 2.4 inches for 0.6 inch diameter prestressing strand. Several western states (Alaska, Washington, Oregon, and others) have used a strand spacing of 1.75 inches center-to-center for 0.5 inch diameter strand with success, and, until recently, have been allowed by the Federal Highway Administration (FHWA) to use this spacing on federal aid projects. However, indications are that the FHWA is considering discontinuing the exception for the 1.75 inch center-to-center spacing in bridges with federal funding.

The original three strand diameter clear spacing requirement was based on two factors: 1) allowance for concrete aggregate passage, and 2) concern for a localized failure in the transfer zone at transfer. Both of these concerns are primarily the result of engineering judgement and have not been sufficiently verified through research. Also, there is presently a concern that a closer strand spacing might increase development requirements and/or reduce nominal moment capacity.

The objective of this research was to investigate the effect of strand spacing on prestressed concrete girder performance. Specifically, the effects on transfer length, development length, and nominal moment capacity of members prestressed with 0.5 inch diameter strand were compared for two strand spacings: 1) the ACI minimum spacing (ACI 7.6.7.1) [1] of 2.0 inches center-to-center, and 2) the 1.75

inch center-to-center spacing used by several states. The effects of concrete strength and confinement on the above quantities were also studied. The objective was accomplished through the testing of fourteen prestressed concrete beam specimens pretensioned with 0.5 inch diameter strand.

The force in a prestressing strand is transferred to the concrete by bond in the end region of a member. The distance from the end of a member over which the effective stress, f_{se}, is fully transferred from the strand to the concrete is called the transfer length. The flexural bond length is the additional embedment length required to develop strand stress due to external load from the effective prestress, f_{se}, to the stress, f_{ps}, at the nominal flexural strength of the member. The development length is the sum of the transfer length and the flexural bond length. Idealized steel stress levels near the end of a member at ultimate load conditions are illustrated in Figure 1-1 with the transfer length, flexural bond length, and development length labeled. In this research, transfer length was determined by measuring surface strains on the cast specimens at transfer, and development length was determined using a trial-and-error scheme. The results of the transfer length measurements and development length tests were compared to ACI design provisions.

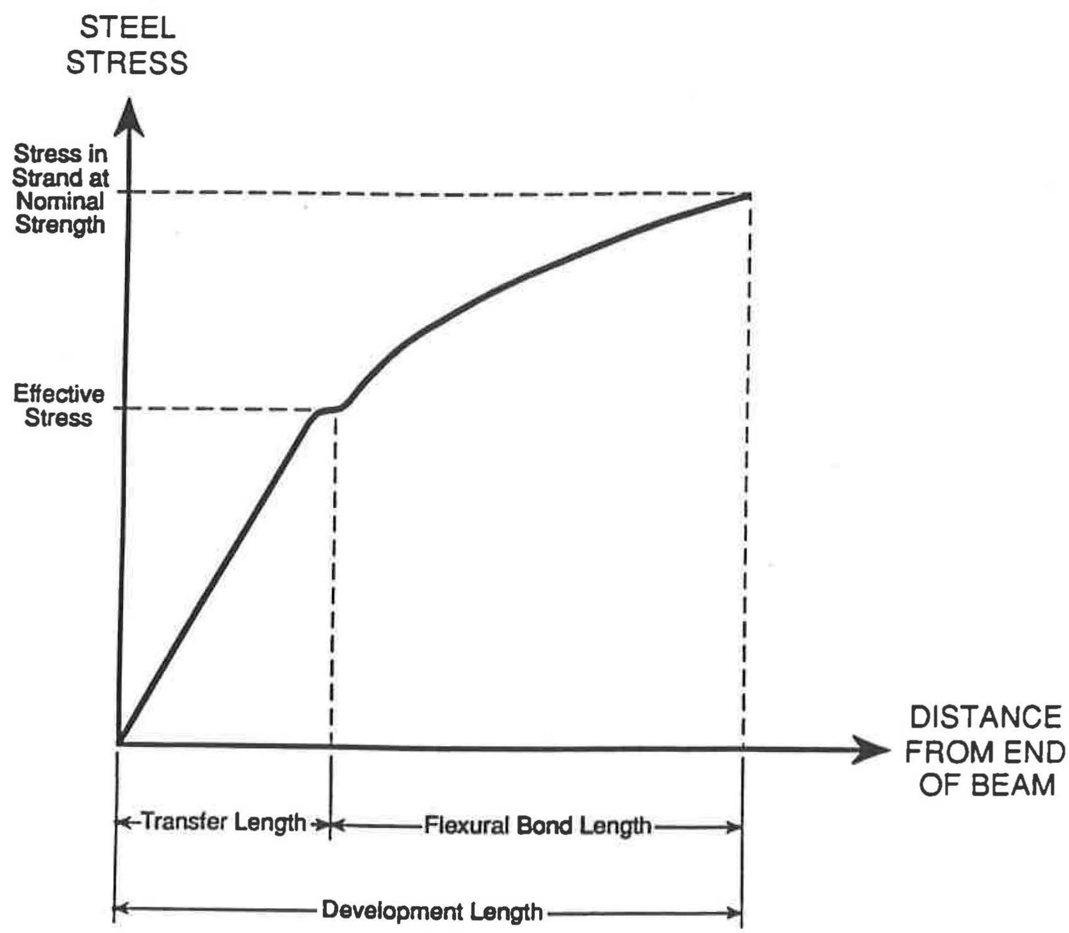


Figure 1-1. Typical Plot of Steel Stress Versus Distance from the End of the Beam Showing Transfer Length, Flexural Bond Length, and Development Length.

Due to the similarity in design provisions specified in the ACI Building Code Requirements for Reinforced Concrete (ACI 318-89) [1] and the AASHTO Standard Specifications for Highway Bridges (1990) [2], only the ACI Code [1] is referenced in this report except when differences between the two occur. Also, unless otherwise noted, strand spacing in this report refers to center-to-center strand spacing.

1.2 Research Significance

For many years several states (Alaska, Washington, Oregon, and others) have used 0.5 inch diameter prestressing strand in pretensioned, prestressed members at a spacing (1.75 inches) smaller than allowed by ACI. These states have been satisfied with the performance of bridge girders made at this smaller spacing. This research verifies that the closer spacing is acceptable which precludes these states from making extensive changes in their design provisions and fabrication procedures.

This finding has implications throughout the prestressed concrete industry. Longer bridge spans are possible through the use of high strength concrete coupled with closer strand spacings.

1.3 Previous Studies

The majority of research conducted in the area of prestressing strand bond over the past forty years has involved the testing of single-strand prisms for transfer length determination and single-strand beams for determining development length. Since the focus of this research is the spacing of prestressing strand in pretensioned, prestressed members, the previous work of pertinent interest are those with specimens containing multiple strands. Studies at The University of Texas at Austin [3], The University of Tennessee at Knoxville [4], and the Structural Research Center of the Florida Department of Transportation [5] have considered the transfer length and/or the development length of specimens with multiple strands. These three studies are the focus of the discussion of previous research in this paper.

1.3.1 The University of Texas at Austin [3]. The most recent study, completed at The University of Texas at Austin in 1992, included the testing of both transfer length prisms and AASHTO-type girders. The transfer length prisms contained either one, three, or five concentric strands of 0.5 inch or 0.6 inch diameter. The AASHTO-type girders contained either five or eight eccentric strands. For all specimens with 0.5 inch diameter strand, a spacing of 2.0 inches was used which is the ACI minimum; however, the 0.6

inch diameter strand was always used at a spacing less than the ACI minimum of 2.4 inches. The spacings used for 0.6 inch diameter strand were 2.0 inches and 2.25 inches. In all specimens a cover of at least 0.5 inches greater than the ACI minimum was used. A total of sixty-five specimens were tested for transfer length, and twenty-eight development length tests were performed.

The prestressing force for the specimens was released by flame cutting for all specimens and the concrete strength at transfer ranged from 4200 psi to 4760 psi. At twenty-eight days of concrete age the concrete strength ranged from 5400 psi to 7530 psi. The strand (270 ksi guaranteed ultimate tensile strength, low-relaxation strand) was stressed to seventy-five percent of the ultimate tensile strength before transfer. Stressing the strand to only seventy-five percent of 270 ksi guaranteed that stresses in the strand at transfer were well below the seventy-four percent of 270 ksi allowed by ACI.

In the research, transfer length was defined as the distance necessary to transfer ninety-five percent of the prestressing force. The authors reported an average transfer length for specimens without debonded strand of 34.9 inches for 0.5 inch diameter strand and 39.0 inches for 0.6 inch diameter strand. These transfer lengths are about fifteen percent less than that calculated by the ACI formula. There was no significant difference in the transfer length of specimens with and without confinement reinforcement, and no cracking of specimens at transfer of prestressing force was reported.

As a result of flexural tests of rectangular specimens and AASHTO-type girders, the authors reported development lengths for 0.5 inch and 0.6 inch diameter strand of 72 inches and 84 inches, respectively. They concluded that these development lengths are adequately predicted by the ACI equation for development length. The primary cause of a bond failure in these tests was flexural cracking within or very near the transfer zone. Also, in several tests the authors noted strand slip of a small magnitude without a complete or general bond failure.

In conclusion, the authors observed that using 0.6 inch diameter strand at a spacing of 2.0 inches had no effect on transfer length, and they reported no difference in behavior of specimens containing 0.6 inch diameter strand at the two spacings during flexural tests.

1.3.2 The University of Tennessee at Knoxville [4]. In the study conducted at The University of Tennessee at Knoxville, twenty-two full-size AASHTO Type I girders were fabricated and tested. The objective of the research was to investigate transfer length and development length of prestressing strand in pretensioned, prestressed concrete.

Four diameters of 270 ksi ultimate tensile strength, low-relaxation strand were used, but only the testing of specimens containing 0.5 inch diameter strand are discussed here. Of the specimens containing 0.5 inch diameter strand, four specimens were made with a strand spacing of 2.0 inches and four with a strand spacing of 1.75 inches. The cover for the strands in the bottom flange was larger than that required by ACI, and the specimens were also heavily confined. The compressive strength of the concrete in these specimens averaged 4820 psi at transfer and 6120 psi at twenty-eight days. Each of these eight beams had eight strands in the bottom flange and two in the top flange. The strands all had a stress of seventy-five percent of 270 ksi immediately after transfer.

The measured transfer lengths (determined by measuring concrete surface strains and using the slope-intercept method) of the specimens averaged 36 inches immediately after transfer with a high of 72 inches and a low of 18 inches. No discernible difference was seen in the transfer lengths of the specimens with the two different strand spacings.

Based on sixteen development length tests, a twenty percent increase to the ACI development length was recommended. The authors also concluded that there was no perceivable difference in the behavior of the girders with the two different strand spacings, and, therefore recommend that ACI allow a center-to-center spacing of three and one half strand diameters for 0.5 inch diameter strand.

1.3.3 The Structural Research Center of the Florida Department of Transportation [5]. In the study conducted at The Structural Research Center of the Florida Department of Transportation, ten AASHTO Type II girders were fabricated and tested to determine transfer length of 0.5 inch and 0.6 inch diameter strand in full-size girders. Both the 0.5 inch diameter strand and the 0.6 inch diameter strand were used at a 2.0 inch strand spacing. Since the 0.6 inch strand was used at a spacing closer than the ACI requirements, only these results are discussed here. Of the ten specimens fabricated, only two contained 0.6 inch diameter strand which was not shielded. The compressive strength of the concrete in these two girders was 5110 psi at transfer of prestressing force, and the strand stress immediately after transfer was 185 ksi (sixty-nine percent of 270 ksi). As in the two previously discussed studies the cover provided for the prestressing strand was greater than that required by ACI.

The authors reported transfer lengths of 30 inches for specimens containing 0.5 inch diameter strand and 34 inches for specimens containing 0.6 inch diameter strand. They concluded that the ACI equation for transfer length appears to be inadequate. The authors defined transfer length as the length necessary to transfer one-hundred percent of the effective prestress to the concrete. As in the other studies there was no cracking at transfer of the specimens with 0.6 inch diameter strand at the closer strand spacing. There was no noticeable difference in transfer length measurements, and it was recommended that the code requirement for spacing be changed to allow 0.6 inch diameter strand at a 2.0 inch spacing.

1.3.4 Summary. In summary, three researchers [3,4,5] have addressed the spacing requirements for prestressing strand through an experimental testing program. All have concluded that the ACI spacing requirement of four strand diameters center-to-center could be reduced somewhat. Two of the researchers [3,5] found no problems with spacing 0.6 inch diameter strand at 2.0 inches, which is three and one third strand diameters. The other author [4] found that spacing 0.5 inch diameter strand at 1.75 inches, which is three and one half strand diameters, was acceptable. The main focus of these testing programs was not to study strand spacing, and in each case a limited number of specimens was tested. In order to supplement this existing body of research information concerning strand spacing, the following testing program was conducted.

CHAPTER 2

2. SPECIMEN DESIGN AND FABRICATION

2.1 Materials

2.1.1 Prestressing Strand. The prestressing strand used was 0.5 inch diameter, seven-wire, 270 ksi guaranteed ultimate tensile strength, low-relaxation strand manufactured to meet ASTM A-416-90A specifications [6]. All strand used in this project came from the same production lot. The modulus of elasticity, one percent elongation yield stress, and ultimate tensile stress as reported by the strand manufacturer were 28,200 ksi, 263 ksi, and 280 ksi, respectively. The strand was lightly rusted, but no pitting was observed. The strand was stored in the lab to prevent further weathering, but the strand was subjected to large amounts of dust and debris from other projects.

2.1.2 Concrete. Two concrete mixes, a normal strength mix design and a high strength mix design, were used so that the effects of concrete strength on transfer and development lengths could be investigated. The normal strength mix was originally proposed to yield a concrete compressive strength at three days of 4500 psi and a twenty-eight day strength of 6000 psi. The high strength mix was originally proposed to yield a concrete compressive strength of 5500 psi at three days and a twenty-eight day strength of 7000 psi. Due to inconsistent strength gains in the two mixes, it became necessary to divide the mixes into two ranges. A batch of concrete that had a strength between 6000 and 8000 psi at the time of the development length tests was classified as normal strength (NS). A batch of concrete that had a strength between 10,000 and 12,000 psi at the time of the development length tests was classified as high strength (HS). In some instances it became necessary to perform development length tests before twenty-eight days in order to keep the strength during testing in the given ranges. Tables 2-1 and 2-2 show the concrete mix proportions for the normal and high strength concrete mixes.

The concrete was batched and delivered by a ready-mix concrete supplier. Superplasticizer was added to the concrete mix to increase workability. Strength gain was not accelerated by heat or other methods. The specimens were moist cured at an ambient temperature of sixty-five to seventy-five degrees Fahrenheit. Concrete cylinders were tested at the time of release, at twenty-eight days, and at the time of each development length test.

Table 2-1. Normal Strength Mix Design.			
MATERIAL	SOURCE	CUBIC YARD PROPORTIONS	ABSOLUTE VOLUME (ft^3)
Cement	Blue Circle	700 lbs.	3.57
Fly Ash	Wansley	125 lbs.	0.83
Stone	Dravo	2000 lbs.	11.29
Sand	Wisener	1132.49 lbs.	6.90
Water		30 gal.	4.00
Air (1.5%)			0.41
Admix	220N	20 oz.	
Admix	Rheobuild	165 oz.	
		Total	27.00

Water/Cement = 0.30
Unit Weight = 155.83 pcf

Table 2-2. High Strength Mix Design.			
MATERIAL	SOURCE	CUBIC YARD PROPORTIONS	ABSOLUTE VOLUME (ft^3)
Cement	Blue Circle	799 lbs.	4.08
Fly Ash	Wansley	125 lbs.	0.83
Stone	Dravo	2000 lbs.	11.29
Sand	Wisener	1049.57 lbs.	6.40
Water		30 gal.	4.00
Air (1.5%)			0.41
Admix	220N	20 oz.	
Admix	Rheobuild	175 oz.	
		Total	27.00

Water/Cement = 0.27
Unit Weight = 156.42 pcf

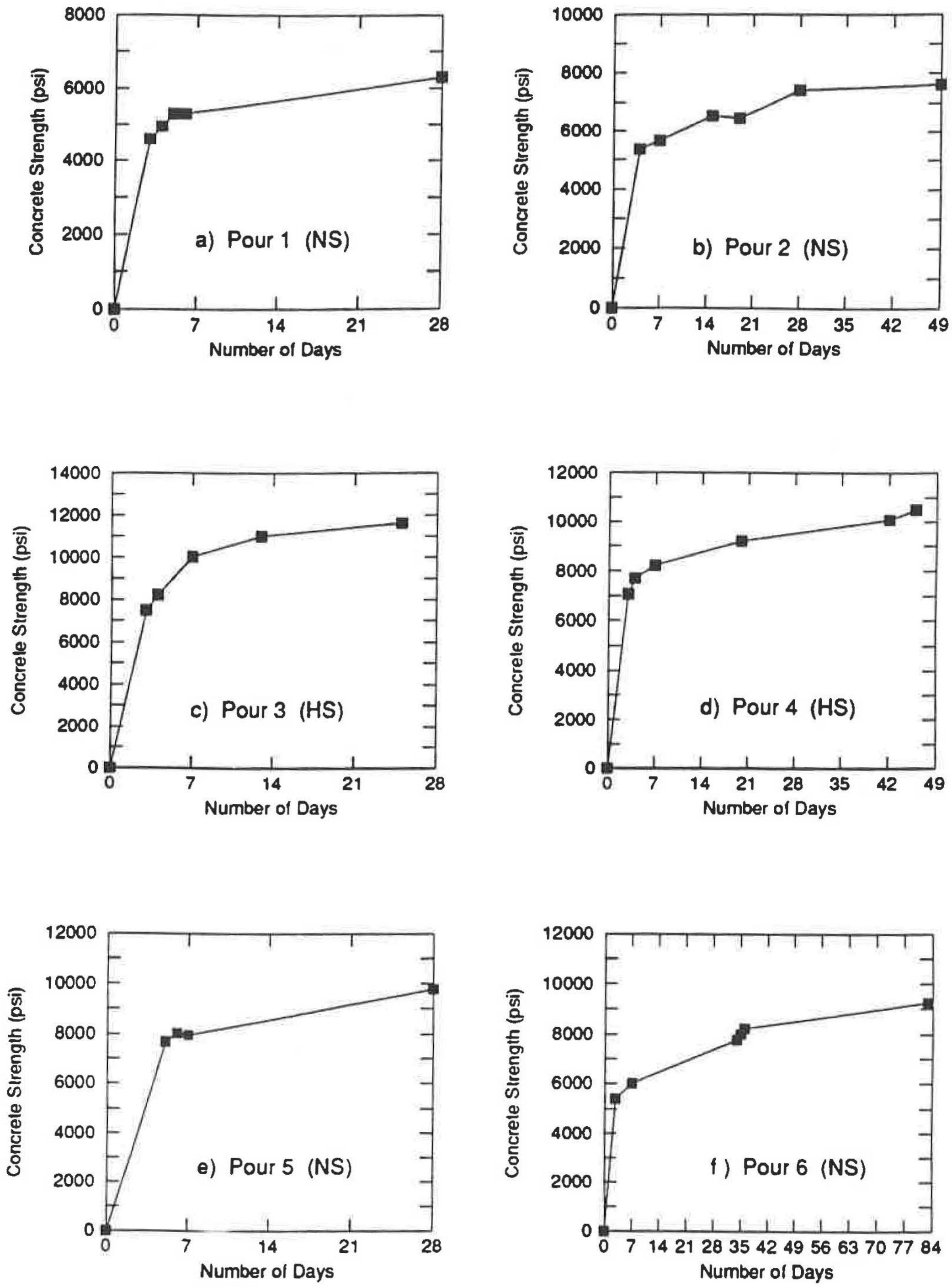


Figure 2-1. Concrete Compressive Strength Gains for Each Pour. (Determined Through Testing of Standard 6 Inch Diameter Concrete Cylinders.)

Table 2-3. Compressive Concrete Strength Summary for Each Pour.

POUR NUMBER {CONCRETE MIX}	BEAM NUMBERS	3-DAY STRENGTH (psi)	7-DAY STRENGTH (psi)	28-DAY STRENGTH (psi)
1 {NS}	1,2,7,8	4600	5310	6310
2 {NS}	3,9	5350	5660	7430
3 {HS}	4,10	7520	10030	11620
4 {HS}	5,11	7080	8220	9210
5 {NS}	6,12	7660	7930	9770
6 {NS}	13,14	5390	6010	7760

Notes: Beams 6 and 12 from pour 5 were classified as NS because the flexural tests were done at seven days when the strength still fell in the "normal strength" category. The twenty-eight day strength is irrelevant since the beam was failed at seven days.

CONCRETE MIX: NS = normal strength mix HS = high strength mix

The compressive strength of the concrete at the time of the development length tests was defined as f'_c for moment strength calculations for each test since this was the concrete strength at which the specimen was actually tested. Any strength gain after this point was irrelevant to the tests. Six batches of concrete were used: four normal strength, and two high strength. Figure 2-1 shows the strength gain history of each pour. Table 2-3 shows the three day, seven day, and twenty-eight day strengths for each pour.

2.2 Design Goals

The goal in the design of the test specimens was to have a cross-section which met all ACI design specifications [1] in a manner to render worst-case transfer and development length tests for an under-reinforced specimen. An under-reinforced section was chosen to achieve the maximum strand stresses at failure in the flexural tests. The specimen was designed to have maximum allowable tendon stresses at transfer, maximum allowable compressive concrete stresses at the bottom fibers at transfer, and minimum allowable cover. This design incorporates maximum stresses with minimum concrete to create a worst-case prestressed specimen.

2.3 Cross-Section Design

Due to lab facility restrictions, nine straight 0.5 inch diameter, seven-wire, 270 ksi guaranteed ultimate tensile strength, low-relaxation strand in a square grid (three rows of three strands, equi-spaced) were used for each specimen. Nine strands was the maximum number that could be safely stressed to eighty percent of 270 ksi in the prestressing bed built in the lab. The equi-spaced grid of nine strands incorporated the effect of strands near the exterior surface of the specimen and the effect of one interior strand surrounded on all sides by other strands to model typical behavior of a prestressed beam. Seven beams had the ACI minimum strand spacing of 2.0 inches and seven beams had a 1.75 inch strand spacing. The cross-sectional dimensions of the prestressed specimen were designed to give a worst-case test of maximum stress with minimum concrete. A T-beam cross-section was used to provide greater stability for the development length tests.

The strand pattern was cast in the web, so the web width was designed as the minimum allowed by ACI specifications. The beams had #4 shear reinforcement and the ACI minimum cover of 1 inch over the stirrups. The beams therefore had web widths of 7.0 and 7.5 inches for the 1.75 and 2.0 inch strand spacings, respectively. These web widths provided for the prestressing grid (two strand spacings and a strand diameter), 0.5 inch on each side of the grid for the #4 rebar, and 1.0 inch on each side for minimum concrete cover.

The flange width and thickness were chosen to satisfy ACI 8.10.4 (flange thickness not less than one-half the web width, and effective flange width not more than four times the web width) [1]. A 5.0 inch flange thickness was used for all beams. The flange widths were chosen as 19.5 inches for the 1.75 inch strand spacing and 20.0 inches for the 2.0 inch spacing. These flange widths allowed all sideforms to be exactly the same, where only the distance between the sideforms was different for the two strand spacings.

Through a trial-and-error process, the beam height and effective depth of prestressing strand were chosen as 22.0 inches and 12.25 inches, respectively. These dimensions were chosen to give the ACI maximum compressive stress of sixty percent of f'_{ci} in the bottom fibers of the smaller cross-section at transfer (ACI 18.4.1) [1]. Figure 2-2 shows the cross-sectional dimensions as designed. Table 2-4 shows the design values for the cross-section in Figure 2-2 for each of the two strand spacings. All calculations were based on three design values: 1) strength of concrete at release, f'_{ci}, of 4500 psi, 2) stress in strand immediately after release, f_{si}, of seventy-four percent of ultimate strength of strand, f_{pu}, and 3) ultimate strength of strand,

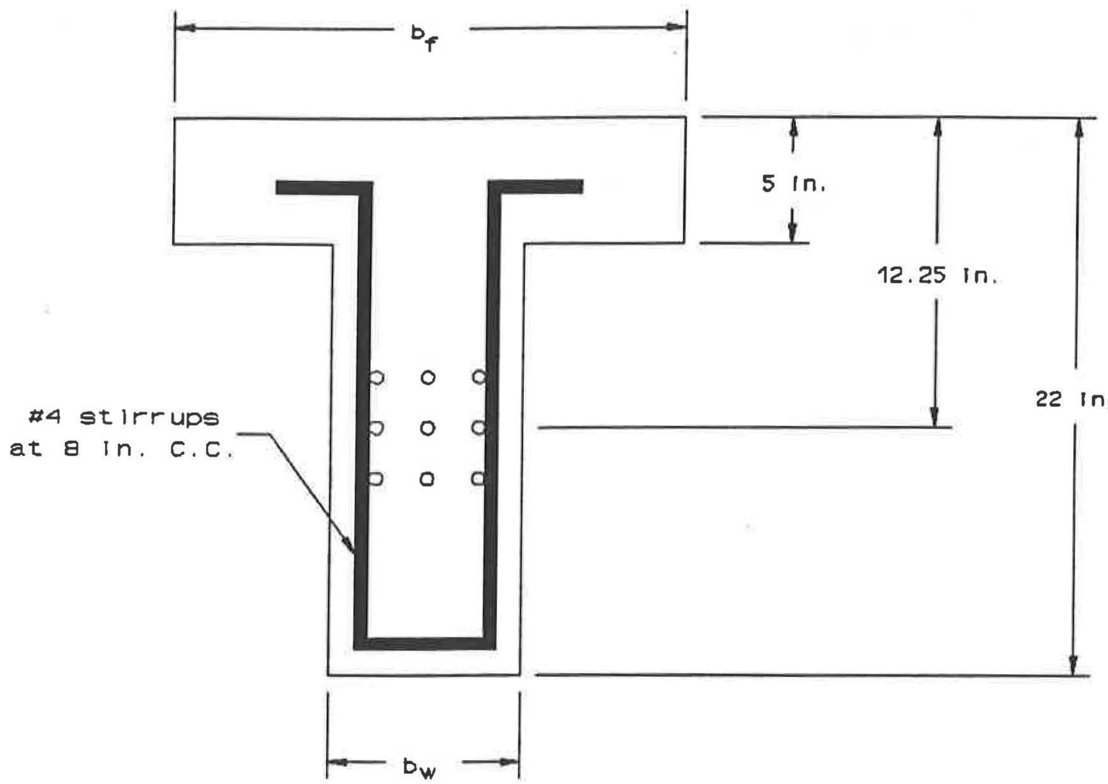


Figure 2-2. Final Cross-Sectional Design Used for All Specimens. Table 2-4 Lists Cross-Sectional Properties and Design Stresses for the Two Strand Spacings (1.75 Inch and 2.0 Inch).

Table 2-4. Calculated Cross-Sectional Properties and Design Stresses for Figure 2-2.

BEAM PROPERTIES		STRAND SPACING 1.75 INCH	STRAND SPACING 2.0 INCH
b_w (in.) Web Width		7	7.5
b_f (in.) Flange Width		19.5	20
A_c (in.^{2}) Area of Concrete		216.5	227.5
I_g (in.^{4}) Gross Moment of Inertia		9554	10060
Section Modulus (in.^{3})	Top S_t	1118	1161
	Bottom S_b	710	754
Location of Centroid of Section From Top Fiber (in.)		8.55	8.66
e (in.) Eccentricity of Strand		3.70	3.59
Designed Concrete Stresses at Transfer (ksi)	σ_{ti} Top Fiber	-0.36	-0.36
	σ_{bi} Bottom Fiber	-2.70	-2.52
ACI Allowable Stresses (ksi)	f_{ti} ACI 18.4.1c	0.40	0.40
	f_{ci} ACI 18.4.1a	-2.70	-2.70

Notes: Negative (-) denotes compression.

Assumed values at transfer used in design of cross-sections:

concrete strength: f'_{ci} = 4500 psi
initial prestress: f_{si} = .74 f_{pu} = 199.7 ksi
ult. strand strength: f_{pu} = 270 ksi

f_{pu}, of 270 ksi. The cross-sections were also checked to insure an under-reinforced section as per ACI 18.8.1 [1] so that the strand stress at ultimate was greater than the one percent elongation yield stress. An under-reinforced section yields the highest strand stresses at failure of the specimen.

2.4 Specimen Fabrication

2.4.1 Stressing the Strand. In order to prestress the strand, a stressing bed was constructed in the lab which allowed two separate 46 foot lines for beam construction. One line was used for the specimens with 1.75 inch strand spacing, and the other line was used for the specimens with 2.0 inch strand spacing.

The strands were stressed one at a time with a hydraulic jack at one end of the stressing bed. The force in each strand was monitored with a load cell at the end opposite to the hydraulic jack. The strands were stressed to provide as near to 32.75 kips of force in each strand as possible. Through calculation of elastic shortening losses, 32.75 kips per strand was determined to be the jacking force needed to provide the ACI maximum transfer stress of seventy-four percent of f_{pu} (ACI 18.5.1) [1]. The AASHTO Specifications only allow for seventy percent of f_{pu} immediately after transfer (AASHTO 9.15.1) [2], so the ACI values were used to obtain the worst-case effects. The 32.75 kips of jacking force per strand provides seventy-nine percent of f_{pu} which conforms to the ACI maximum jacking stress of eighty percent of f_{pu} (ACI 18.5.1) [1].

Table 2-5 shows the actual jacking force data for each beam just before the concrete was placed. As can be seen in Table 2-5 the jacking stresses were nearly eighty percent of 270 ksi as allowed by ACI (ACI 18.5.1) [1]. If compared to the actual ultimate strength of the strand of 280 ksi, the ratio dropped to seventy-seven percent of ultimate.

2.4.2 Pre-Pour Setup. Once the strands were stressed the formwork was placed in position and bolted in place. The shear reinforcement and the confinement loops (if used) were then placed on 8 inch centers throughout the beams and tied in place. The shear reinforcement is shown in Figure 2-2. The confinement loops were square loops of #4 rebar made to closely encompass the strand pattern.

In order to measure surface strains in the concrete at transfer, small threaded inserts were embedded in the side of the web of each beam. The threaded inserts were bolted along the length of the inside of the sideforms on 2.0 inch centers at the depth of the centroid of the strand pattern.

2.4.3 Placing the Concrete. The concrete was batched and delivered by a local ready-mix plant in the quantity of six to seven cubic yards per pour. Once the slump of the

Table 2-5. Jacking Force Data for Each Beam.

POUR #	1.75 INCH STRAND SPACING			2.0 INCH STRAND SPACING		
	BEAM #'S	JACKING FORCE FOR 9 STRANDS (kips)	AVERAGE JACKING STRESS (ksi) $\{f_{pj}/f_{pu}\}$	BEAM #'S	JACKING FORCE FOR 9 STRANDS (kips)	AVERAGE JACKING STRESS (ksi) $\{f_{pj}/f_{pu}\}$
1	1,2	292.71	212.6 {0.787}	7,8	292.46	212.4 {0.787}
2	3	296.05	215.0 {0.796}	9	298.05	216.4 {0.801}
3	4	295.40	214.5 {0.794}	10	297.88	216.3 {0.801}
4	5	299.03	217.2 {0.804}	11	296.05	215.0 {0.796}
5	6	300.11	217.9 {0.807}	12	299.41	217.4 {0.805}
6	13	299.85	217.8 {0.807}	14	298.16	216.5 {0.802}
	Avg.	297.19	215.8 {0.799}	Avg.	297.00	215.7 {0.799}

Notes: Forces measured with load cells just before concrete placement.
f_{pj} = average jacking stress
f_{pu} = 270 ksi

concrete was checked to ensure adequate workability, the concrete was placed in the formwork and internally vibrated. The concrete was placed in the forms in three lifts: 1) the first lift filled the formwork to just above the top row of strands, 2) the second lift filled the forms to the top of the web, and 3) the third lift filled the flange. The concrete was thoroughly vibrated during each lift. The tops of the flanges were then finished to a smooth surface, and the lifting hooks were put in position. Approximately twenty concrete cylinders were made for each pour.

2.4.4 Curing the Concrete. As soon as the tops of the beams were finished, they were covered with polyethylene sheets until transfer. The top surface of the beams were kept moist to provide a high humidity environment for curing under the polyethylene sheets and to avoid shrinkage cracking. The concrete cylinders were cured in the same manner as the beams. Figure 2-1 shows the results of the concrete cylinder strength tests. Table 2-3 shows the three day, seven day, and twenty-eight day strengths for each pour.

2.4.5 Transfer of Prestress. After the concrete surpassed the designed release strength, the prestressing force was transferred using an acetylene torch. To prevent over-stressing of the beams during release, the strands were cut individually in the following manner: one-by-one the four corner strands were cut, then the four remaining exterior strands were cut, and then the center strand was cut. No cracking of any beam was observed at transfer. After the strands were cut, the screws fastening the threaded inserts to the sideforms were taken out, and the formwork was removed.

Table 2-6 shows the calculated strand stresses for each beam immediately after transfer. The stress, f_{si}, represented in Table 2-6 was the calculated stress in the strand immediately after transfer taking into account the losses due to elastic shortening of the beam. As can be seen in Table 2-6 the stresses in the strand at transfer, f_{si}, were approximately seventy-seven percent of 270 ksi which is larger than the seventy-four percent allowed by ACI (ACI 18.5.1) [1]. But if the transfer stress, f_{si}, was compared to the actual ultimate strength of the strand of 280 ksi, the ratio was just below the seventy-four percent allowed by ACI. The strand stress was intended to push the envelope of the maximum ACI standards to provide the worst-case stresses in the specimens.

Table 2-7 shows the calculated concrete stresses for each beam immediately after transfer. In Table 2-7 σ_{ti} and σ_{bi} were the calculated stresses at the top and bottom concrete fibers, respectively, due to the stress, f_{si}, in the strand immediately after transfer. As can be seen all

Table 2-6. Calculated Strand Stresses at Transfer for Each Beam.

POUR NUMBER	1.75 INCH STRAND SPACING		2.0 INCH STRAND SPACING	
	BEAM NUMBERS	f_{si} (ksi) $\{f_{si}/f_{pu}\}$	BEAM NUMBERS	f_{si} (ksi) $\{f_{si}/f_{pu}\}$
1	1,2	202.1 {0.749}	7,8	202.7 {0.751}
2	3	205.4 {0.761}	9	207.5 {0.769}
3	4	206.8 {0.766}	10	209.1 {0.774}
4	5	209.1 {0.774}	11	207.6 {0.769}
5	6	209.9 {0.777}	12	209.0 {0.777}
6	13	208.7 {0.773)	14	208.1 {0.771}
	Average	207.0 {0.767}	Average	207.3 {0.768}

Notes: f_{si} = calculated stress in strand immediately after transfer
f_{pu} = 270 ksi

Table 2-7. Calculated Concrete Stresses for Each Beam Immediately After Transfer.

POUR #	f'_{ci} (psi)	1.75 INCH STRAND SPACING			2.0 INCH STRAND SPACING			ACI f_{ci} (ksi)
		BEAM #	σ_{ti} (ksi)	σ_{bi} (ksi)	BEAM #	σ_{ti} (ksi)	σ_{bi} (ksi)	
1	5310	1,2	-0.36	-2.74	7,8	-0.37	-2.55	-3.18
2	5350	3	-0.37	-2.78	9	-0.37	-2.61	-3.21
3	8220	4	-0.37	-2.80	10	-0.38	-2.63	-4.93
4	7690	5	-0.38	-2.83	11	-0.37	-2.61	-4.61
5	7660	6	-0.38	-2.84	12	-0.38	-2.64	-4.60
6	6010	13	-0.38	-2.83	14	-0.37	-2.62	-3.61

Notes: Negative (-) denotes compression.

f'_{ci} = actual compressive concrete strength at transfer
σ_{ti} = calculated stress in top fiber of concrete immediately after transfer
σ_{bi} = calculated stress in bottom fiber of concrete immediately after transfer
f_{ci} = ACI allowable compressive stress at transfer based on actual f'_{ci} [ACI 318-89, Sec. 18.4.1a]

concrete stresses conformed to the ACI maximum compressive stress of sixty percent of f'_{ci}, the concrete strength at the time of transfer (ACI 18.4.1) [1].

2.4.6 Summary of Specimens. Table 2-8 gives a general description of each beam cast for this project. Each beam is identified by a number (1 through 14). Eight specimens of unconfined, normal strength mix were cast (four each of 1.75 inch and 2.0 inch strand spacing). Four specimens of unconfined, high strength mix were cast (two each of 1.75 inch and 2.0 inch strand spacing). Two specimens of confined, normal strength mix were cast (one each of 1.75 inch and 2.0 inch strand spacing).

Table 2-8. General Description of Each Beam.

BEAM NUMBER	POUR NUMBER	STRAND SPACING (in.)	CONCRETE MIX	CONFINEMENT	BEAM LENGTH (ft.)
1	1	1.75	Normal	Unconfined	22.0
2	1	1.75	Normal	Unconfined	22.0
3	2	1.75	Normal	Unconfined	39.5
4	3	1.75	High	Unconfined	39.5
5	4	1.75	High	Unconfined	39.5
6	5	1.75	Normal	Unconfined	39.5
7	1	2.0	Normal	Unconfined	22.0
8	1	2.0	Normal	Unconfined	22.0
9	2	2.0	Normal	Unconfined	39.5
10	3	2.0	High	Unconfined	39.5
11	4	2.0	High	Unconfined	39.5
12	5	2.0	Normal	Unconfined	39.5
13	6	1.75	Normal	Confined	39.5
14	6	2.0	Normal	Confined	39.5

Notes: Concrete Mix: Normal - 6,000 psi to 8,000 psi compressive concrete strength at time of flexural tests.
High - 10,000 psi to 12,000 psi compressive concrete strength at time of flexural tests.

CHAPTER 3

3. TESTING, INSTRUMENTATION, AND DATA REDUCTION

3.1 Transfer Length Tests

The purpose of measuring surface strains of the beams was to determine the transfer length of specimens with 0.5 inch diameter prestressing strand. The effects of strand spacing, concrete strength, and confinement on the transfer length were studied. The transfer length is defined as the length of embedment needed for one-hundred percent of the effective strand stress to be transferred to the concrete. This statement implies that once the strand stress is fully transferred to the concrete, the stress in the concrete and, therefore, the strain in the concrete is constant. Measuring and plotting the surface strains versus the distance from the end of the beam, therefore, shows the region of one-hundred percent transfer as a plateau in the strain measurements. In order to measure surface strains, an extensometer was used to measure the strain between threaded inserts embedded in the sides of the specimens.

3.1.1 Threaded Inserts. The 0.375 inch long threaded inserts embedded in the sides of the web had a 0.25 inch outside diameter and 0.125 inch inside diameter. The inserts were embedded on 2.0 inch centers along the length of the web at the height of the centroid of the strand pattern starting 1.0 inch from the end of the beam as shown in Figure 3-1. Fastening the inserts flat against the sideforms before the concrete was poured allowed the inserts to become embedded flush with the sides of the web. When the concrete was poured and cured, the screws holding the inserts to the sideforms were taken out, and the formwork was removed. Only the flush, flat ends of the inserts were visible with the 0.125 inch diameter holes to be used as endpoints for the strain measurements.

3.1.2 Measurements With Extensometer. The digital extensometer used for making the surface strain measurements had a resolution of 0.0001 inches. In order to obtain the most accurate results, the longest possible gage length of 10.0 inches was chosen. The extensometer was first calibrated to 10.0 inches using the calibration bar provided by the manufacturer. Once the extensometer was calibrated, measurements between threaded inserts were made immediately before and immediately after the transfer of the prestressing force, and the measurements were recorded on computer in a worksheet file. Figure 3-2 shows the

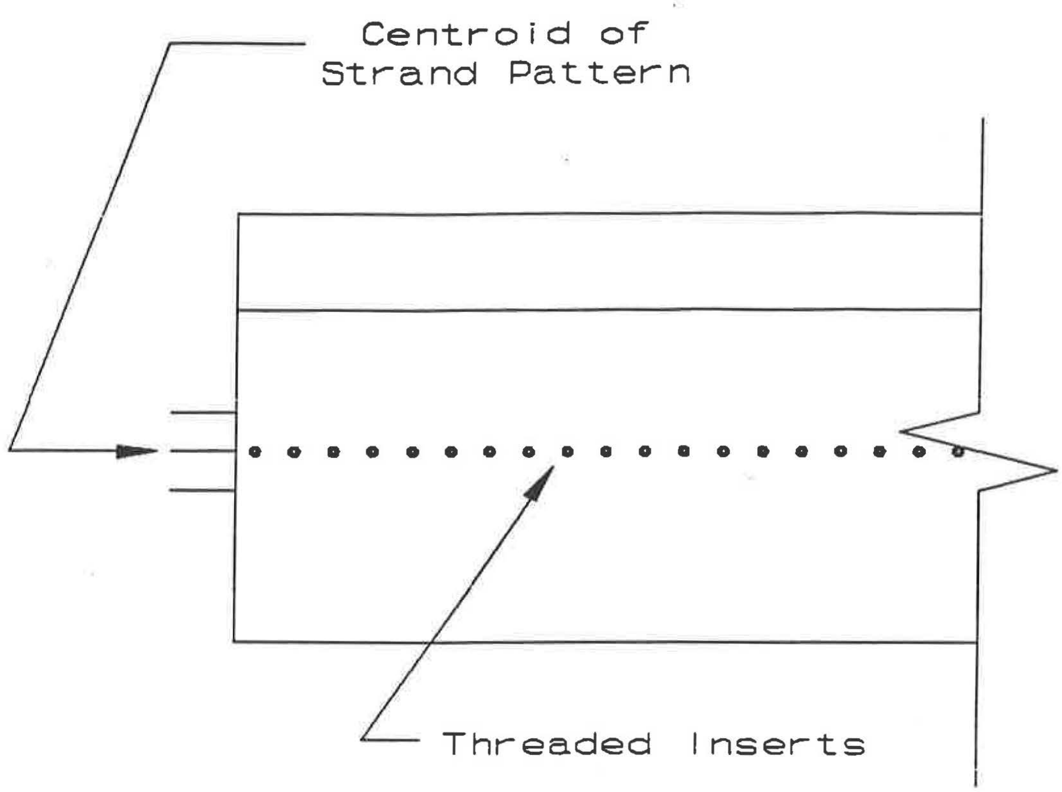


Figure 3-1. Partial Side View of a Typical Beam Showing Orientation of Threaded Inserts.

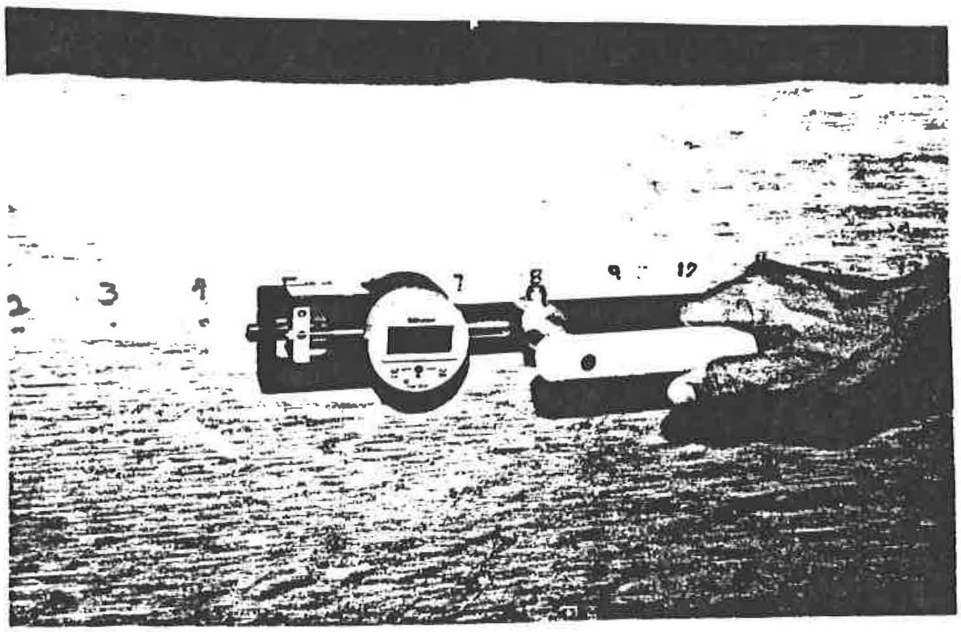


Figure 3-2. Measuring Surface Strains Between Threaded Inserts With a Digital Extensometer.

extensometer as it was used in measuring between two threaded inserts. Measurements were typically taken at seven days and twenty-eight days after transfer, also. The posts on each end of the extensometer were snugly placed into the holes of the threaded inserts and the distances recorded. Each measurement before transfer was taken twice. If the two measurements did not agree within 0.001 inches, they were measured again. The average of the two measurements agreeing within 0.001 inches was used as the initial distance between points. Since the gage length was 10.0 inches and the threaded inserts were on 2.0 inch centers, the measurements overlapped.

Readings before transfer were subtracted from readings after transfer to obtain the change in distance between inserts over the 10.0 inch gage length. The change in distance between inserts was then divided by 10.0 inches to obtain the average strain over that gage length. The average strain for each 10.0 inch gage length was defined to be the strain for an element at the midpoint of that gage length. This method provided strain measurements every 2.0 inches along the beam starting 6.0 inches from the end (the first insert was 1.0 inch from the end and the midpoint of the first gage length was 5.0 inches from the first insert).

3.1.3 Estimated Strain Plateau and Final Transfer Length. Once the strains were calculated, plots such as Figure 3-3(a) of surface strain versus distance from the end of the beam were made. Figure 3-3 was produced from the surface strain data of end B of Beam 14 (2.0 inch strand spacing, confined, normal strength mix). The graph shows the actual measurements taken at the time of transfer. It was a concern that the strain due to the self-weight moment of the beam (due to the simple support condition caused by camber) could affect the strain measurements. The self-weight strain at the effective depth of strand was investigated and found to be at least an order of magnitude smaller than the prestressing strain.

Visually inspecting the plot, the point at which the graph seemed to plateau was marked. This point is illustrated in Figure 3-3(a) by the vertical dashed line. A very simple statistical analysis of the "plateau points" was then performed in order to eliminate "bad points". All points to the right of the vertical dashed line ("plateau points") in Figure 3-3(a) were used to calculate an average strain and standard deviation for the plateau. Plotting the average, average plus one standard deviation, and average minus one standard deviation shown by the horizontal dashed lines in Figure 3-3(a), the points on the plateau outside the standard deviation lines were dropped. These "bad

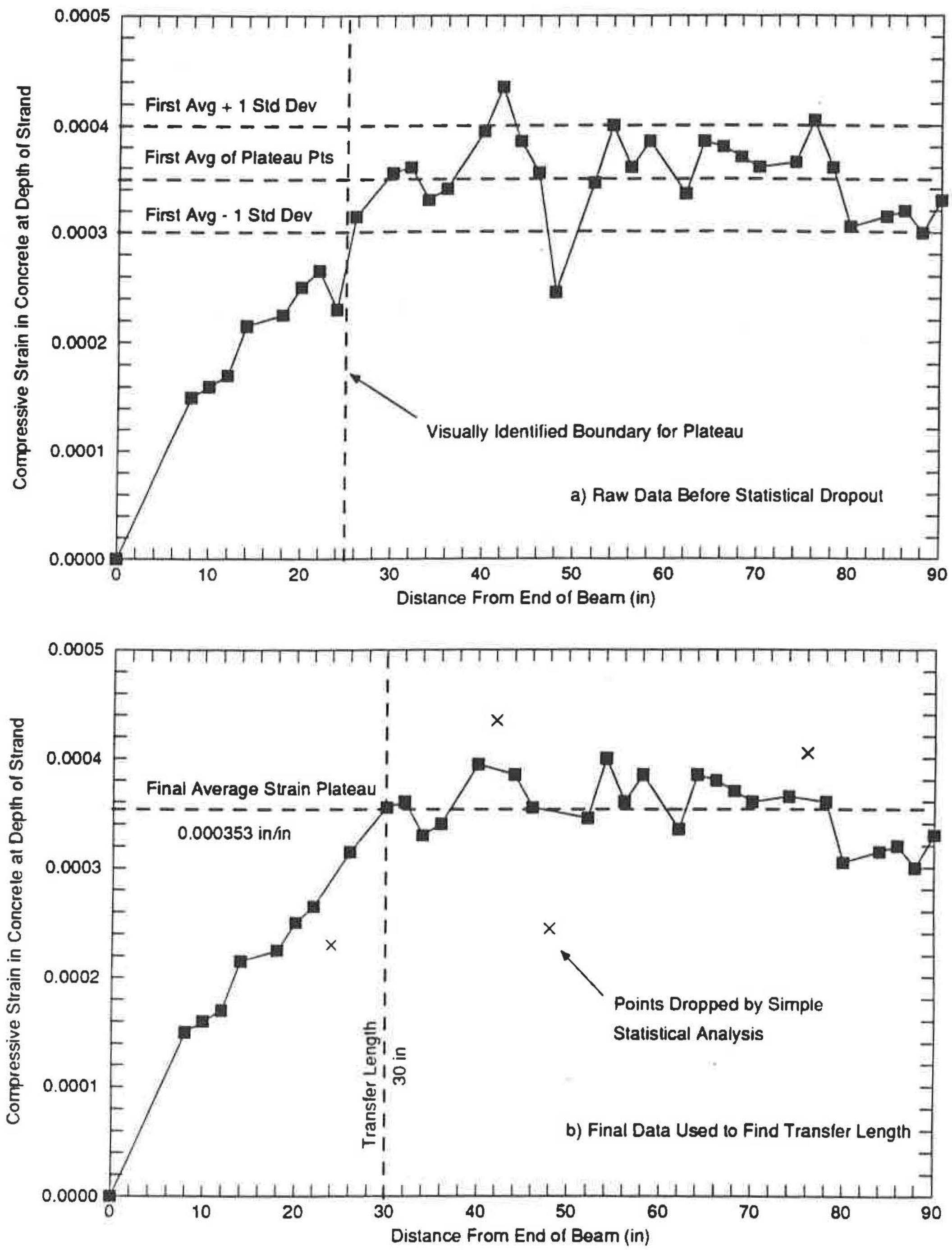


Figure 3-3. Typical Surface Strain Measurements.
a) Raw Data Before Statistical Dropout of "Bad Points",
b) Reduced Data Used to Find Transfer Length.
(Beam 14, End B, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

points" were generally caused by concrete in the holes of the threaded inserts. With concrete in the holes of the threaded inserts, the posts of the extensometer could not be snugly or consistently placed in the same position.

Figure 3-3(b) shows the final product of the surface strain measurements of end B of Beam 14. The X's show the dropped points. A new average strain of the plateau points excluding the dropped points was calculated and is illustrated by the horizontal dashed line in Figure 3-3(b). This final average plateau strain was then used to define the transfer length of the beam. The first point of the plot to reach the average strain plateau was chosen as the transfer length as shown by the vertical dashed line in Figure 3-3(b). Plots of all raw surface strain data at intervals of time after transfer can be found in Appendix A. Plots of reduced surface strain data immediately after transfer showing the strain plateau and transfer length can be found in Appendix B. The effects of three variables on the transfer length were studied: 1) strand spacing, 2) concrete compressive strength, and 3) confinement.

3.2 Development Length Tests

The purpose of the flexural tests of the T-beams was to determine the development length and ultimate moment capacity of specimens with 0.5 inch diameter prestressing strand. The effects of strand spacing, concrete strength, and confinement on development length were studied. The development length is defined as the shortest embedment length from the end of the specimen at which the nominal moment capacity of the specimen can be achieved. Any section inside the development length cannot develop nominal moment capacity because the length of bond is not sufficient to accommodate the significantly higher strand stresses during loading. The strand slips through the concrete before a section inside the development length reaches nominal moment capacity.

The four 22 foot beams were tested only once in flexure at full-length spans. The ten 39.5 foot specimens were each tested twice in flexure. The 39.5 foot specimens were tested on each end over spans less than full length. This practice allowed an undisturbed length of beam after the first test, and the beam was turned around and tested on the other end. Figure 3-4 shows the set-up for a typical flexural test, and Figure 3-5 shows a typical flexural test in progress.

3.2.1 Embedment Length. The first decision to be made before each test was the length of embedment to be tested. The embedment length was defined as the distance from the end of the beam being tested to the point of load. Since the beam was simply-supported and loaded at one point, the

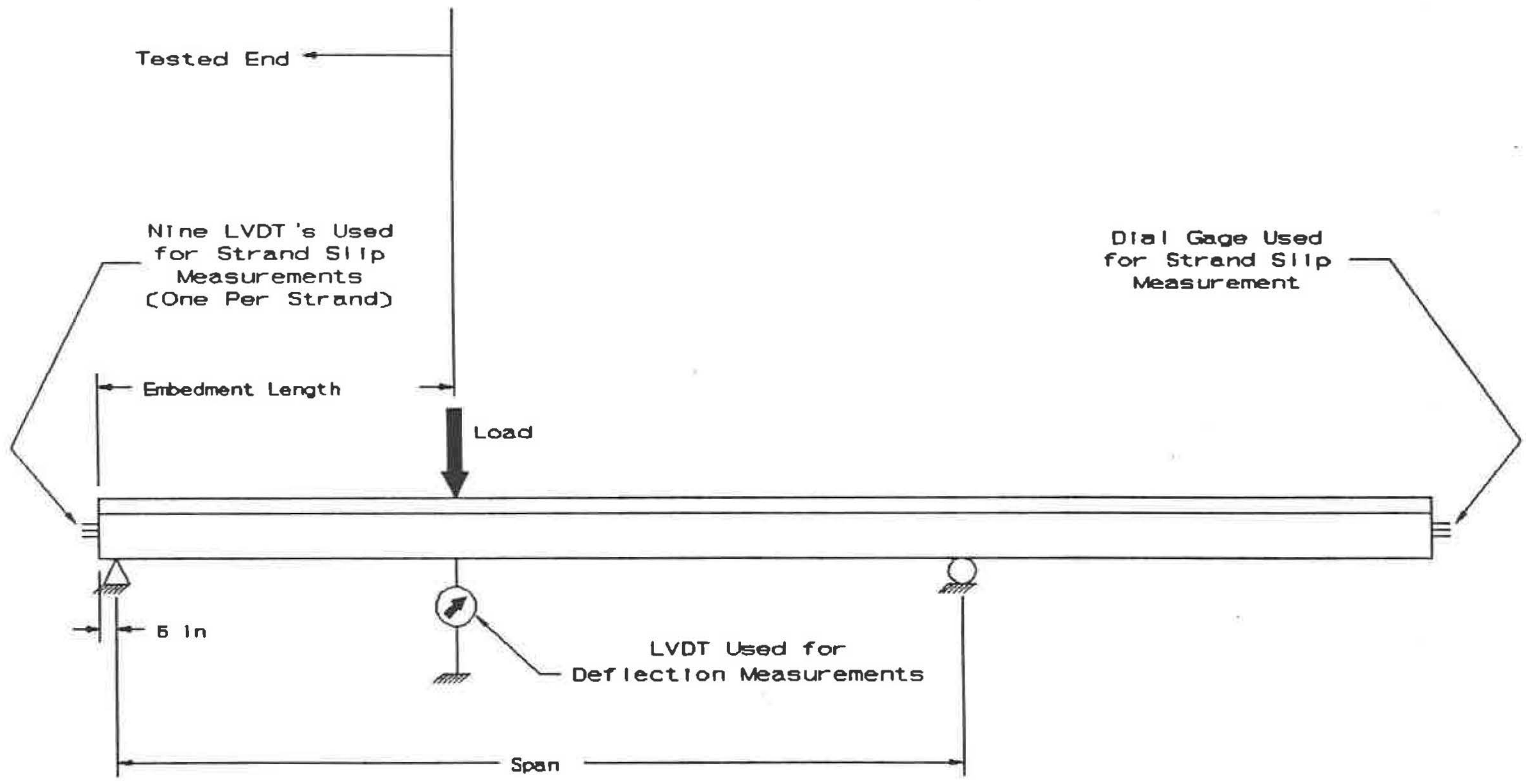


Figure 3-4. Typical Flexural Test Set-Up.

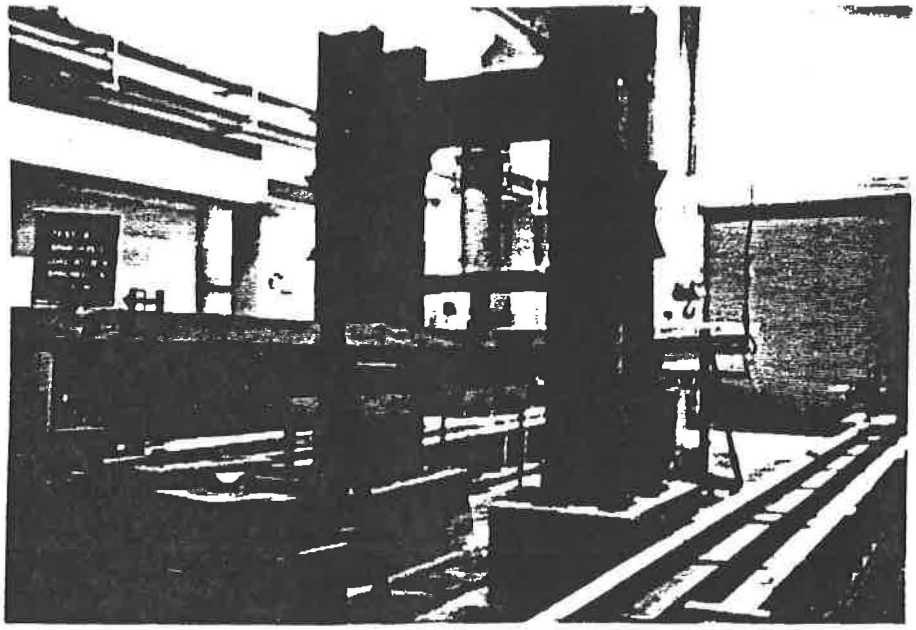


Figure 3-5. Typical Flexural Test in Progress.

load point was the critical section of maximum moment. The distance from the end of the beam to the critical section was the embedment length being tested.

The first embedment length tested was chosen arbitrarily as the best estimation of the development length. Once an embedment length was tested, the outcome of the test determined the next embedment length to be tested. If the specimen achieved nominal moment capacity with little or no slip, and crushing of the concrete was observed, the embedment length was equal to or greater than the development length. The embedment length for the next test was decreased in this case. If the specimen failed to achieve nominal moment capacity due to strand slip, the embedment length was less than the development length, and the embedment length for the next test was increased. This procedure was continued until the minimum embedment length for which nominal moment capacity was identified. This distance was defined as the development length.

3.2.2 Loading the Beam. The beams were simply-supported with a pin support at one end and a roller support at the other end as shown in Figure 3-4. The load was applied at a single point with a 600 kip capacity hydraulic jack. In order to obtain load data, a 300 kip capacity load cell was placed in series with the hydraulic jack. Through calibration tests with a Tinius-Olsen load machine, the load cell was determined to provide load values accurate to within 100 pounds.

Load was applied to the specimens in increments of 2.5 kips until the formation of the first crack, and then the increment was increased to 5.0 kips for the remainder of the test. Each test took forty-five minutes to one hour to load the specimen to failure. Whether due to slip of the strand, crushing of the top surface of the concrete, or a combination of the two, failure was defined as the point at which the load could not be increased.

3.2.3 Beam Deflection. In order to measure deflections for the tests, an LVDT (linear variable differential transformer) with a 2.0 inch travel was placed below the load point of the specimen as shown in Figure 3-4. Through calibration tests with a digital micrometer accurate to 0.0001 inches, the deflection LVDT was determined to provide readings accurate to within 0.002 inches.

The LVDT was placed below the beam at the point of load with the plunger almost fully extended to the bottom of the web. As the beam deflected downward the plunger was retracted into the housing of the LVDT. As the plunger moves the voltage change can be monitored and converted to displacements. If the test specimen deflected more than the allowed 2.0 inches, the test was stopped, and the LVDT was moved down until the plunger was again almost fully extended. The test was continued at that point. The LVDT was moved as many times as necessary until the end of the test. Beam deflection plots for each test can be found as a part of Appendix C.

__3.2.4 Strand Slip__. In order to measure the slip of the strands during a test, each protruding strand on the end of the beam being tested was outfitted with an LVDT with a 0.5 inch travel as shown in Figure 3-6. Through calibration tests with a digital micrometer accurate to 0.0001 inches, each slip LVDT was determined to have an accuracy within 0.0005 inches.

Each strand protruded approximately 1.0 inch from the end of the beam. A cap with a smooth, flat surface was snugly fit to the end of each strand to provide an even surface on which the plunger of the slip LVDT rested. Each slip LVDT was mounted so that the plunger was approximately half retracted. As the strand slipped the spring-loaded plunger extended to stay in contact with the surface of the strand cap. The change in voltages were converted to displacements and recorded. The apparatus measuring slip was never moved during a test because the beam developed a full slip failure well before 0.25 inches of slip occurred. The slip of the strands at the end opposite the tested end were monitored with dial gages accurate to 0.0001 inches, but no measurable slip occurred for any test. Through

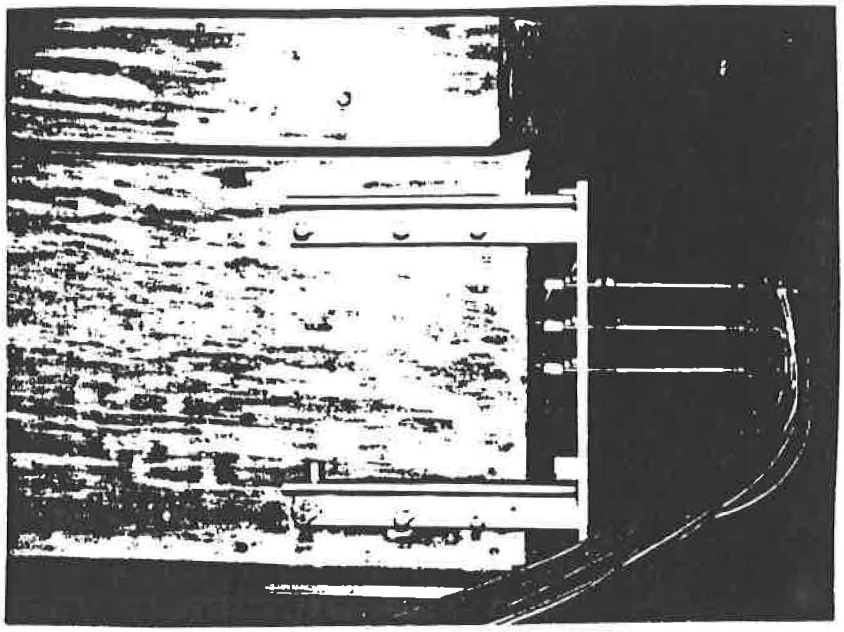


Figure 3-6. Mounting Apparatus for Measuring Slip of Prestressing Strands.

observation of our data a slip of more than 0.01 inches displayed a severe loss in bond between strand and concrete. Plots of strand slip for each test can be found as a part of Appendix C.

3.2.5 Data Acquisition System. In order to collect large quantities of data all test readings were taken by a computer-driven data acquisition unit. The data acquisition unit took continuous data samples during each test. Each data set included the time of day, the displacements of the nine slip LVDT's, the displacement of the deflection LVDT, and the load measured by the load cell. The data acquisition system took samples at the rate of 120 data sets per minute. Two full data sets of the twelve elements (time, nine slips, deflection, and load) were taken each second and stored to computer disk for data reduction. The data acquisition system read the voltage outputs from all LVDT's and the load cell and automatically converted them to the proper units of inches and kips, respectively.

3.2.6 Specimen Cracking. After each load increment the load was held constant, and the beams were inspected. Cracks and crack extensions were marked and labeled with the current magnitude of load. Crushing of the top surface of concrete was also marked when it occurred. Full crack profiles for each flexural test can be found in Appendix D.

3.2.7 Data Reduction. Once a test was finished and the data had been stored on computer disk, some data reduction was necessary to provide clear information. The applied load was converted to the moment at the section below the load. The initial reading of an LVDT was subtracted from all following readings to provide the absolute displacement of the slip or deflection being measured. For each test the plot of moment versus slip for all nine strands and the plot of moment versus beam deflection was made. These plots are given in Appendix C.

3.2.8 Final Development Length. When a test was completed and inspected, it was labeled as one of three failure types: 1) bond failure, 2) flex/slip failure, or 3) flexural failure. A bond failure was defined as a failure occurring due to excessive slip of the strands without reaching nominal moment capacity of the section. Figure 3-7 shows a plot of a typical bond failure produced in Test 1 (beam 2, end A, 1.75 inch strand spacing, normal strength mix, unconfined, 96 inch embedment length). A flex/slip failure was defined as a failure due to crushing of the top fibers of concrete by reaching nominal moment capacity with slip greater than 0.01 inches of any strand occurring at the same time. A slip of 0.01 inches was found to be the point at which a significant loss in bond between strand and concrete occurred. Figure 3-8 shows a plot of a typical flex/slip failure produced in Test 12 (beam 9, end B, 2.0 inch strand spacing, normal strength mix, unconfined, 150 inch embedment length). A flexural failure was defined as a failure due to crushing of the top fibers of concrete by reaching nominal moment capacity without any measurable slip of the strand. Figure 3-9 shows a plot of a typical flexural failure produced in Test 18 (beam 10, end B, 2.0 inch strand spacing, high strength mix, unconfined, 168 inch embedment length).

When all of the tests were completed the development length was defined to be in the range bounded by the longest embedment length for which a bond failure occurred and the shortest embedment length for which nominal moment capacity was attained (flex/slip or flexural failure). The effects of three variables on development length were studied: 1) strand spacing, 2) concrete strength, and 3) confinement. Table 3-1 gives an outline of all flexural tests performed.

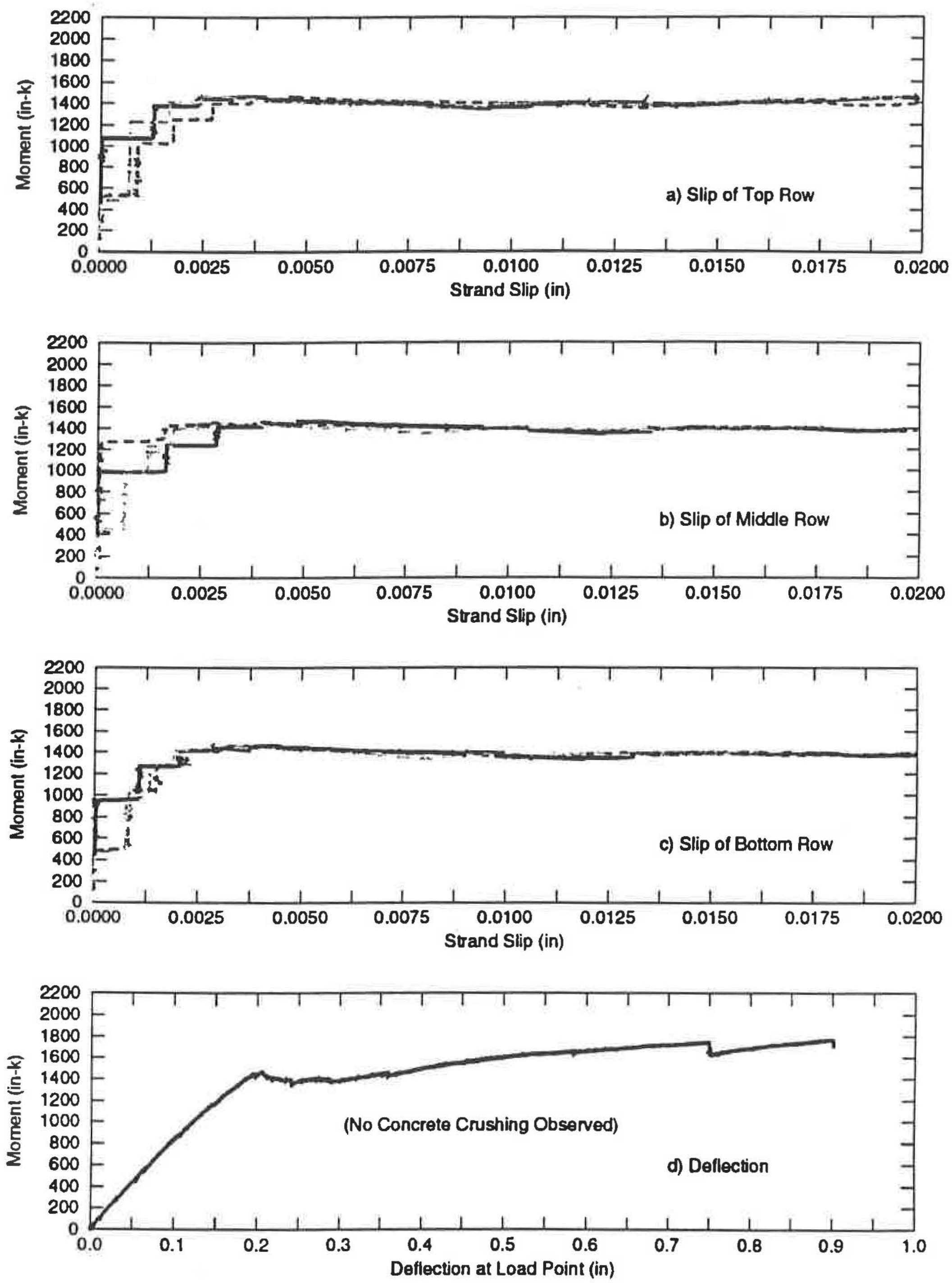


Figure 3-7. Flexural Test Data for a Typical Bond Failure. (Test 1, Beam 2, End A, 1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 96 Inch Embedment Length.)

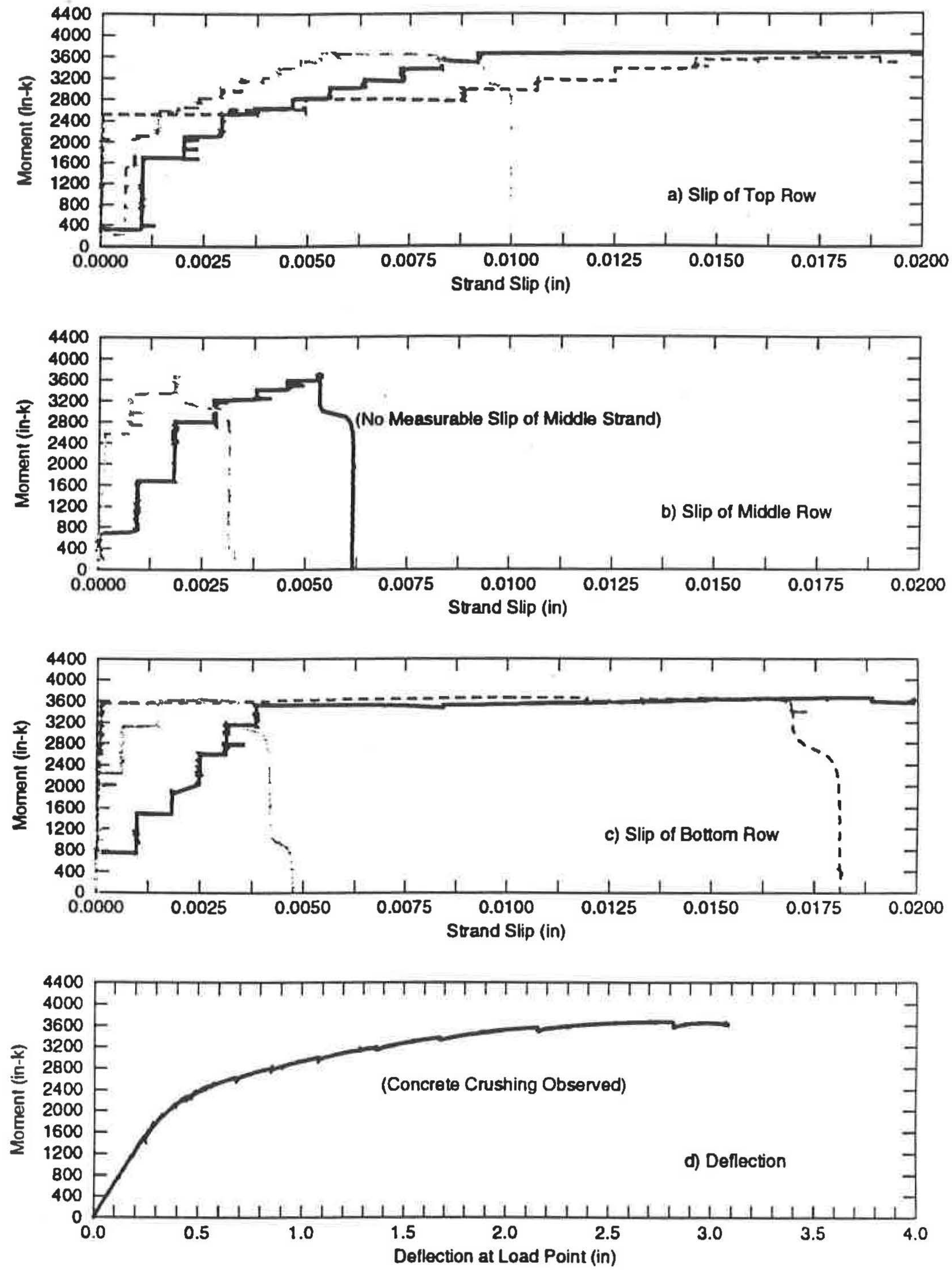


Figure 3-8. Flexural Test Data for a Typical Flex/Slip Failure. (Test 12, Beam 9, End B, 2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length.)

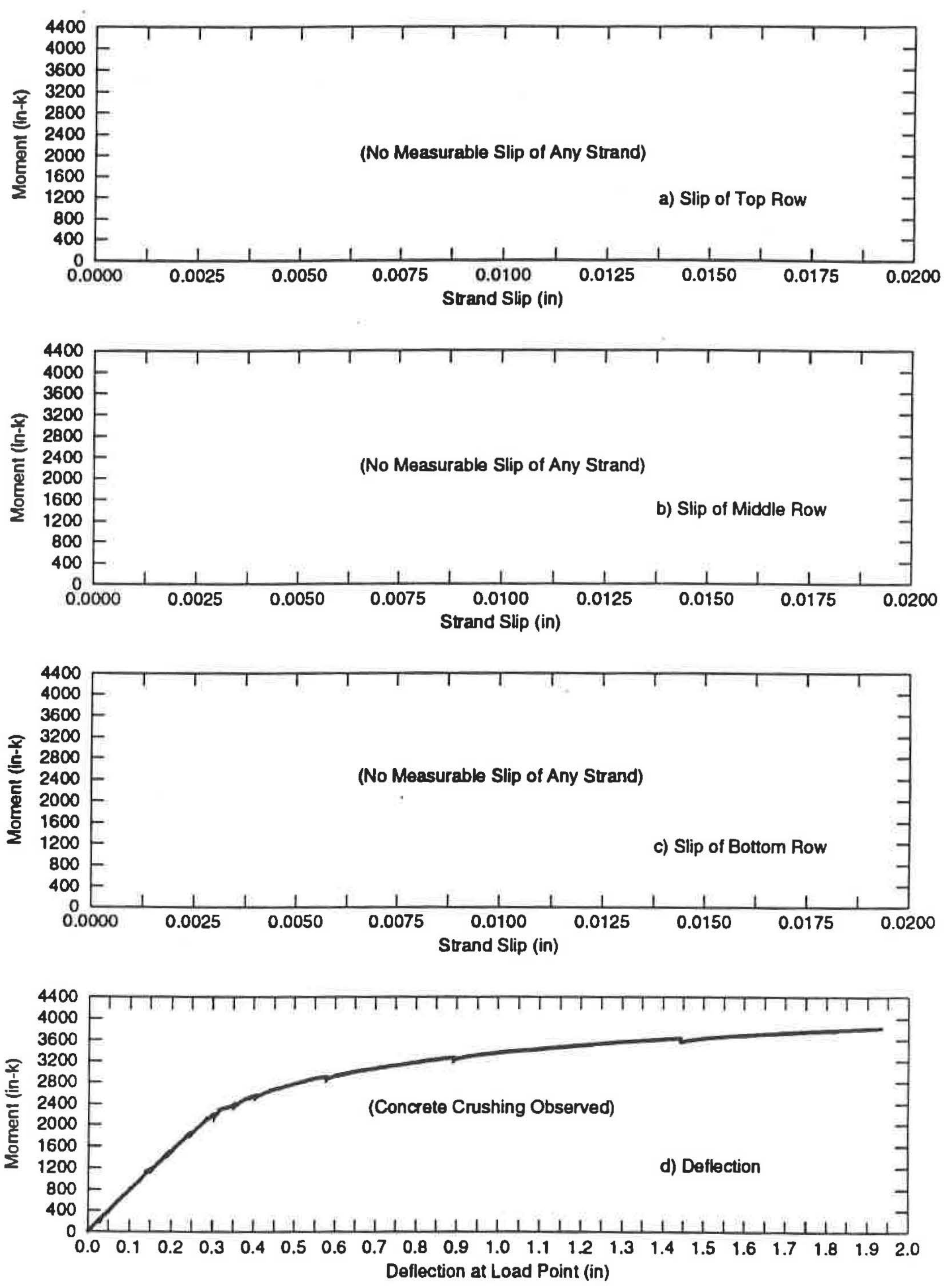


Figure 3-9. Flexural Test Data for a Typical Flexural Failure. (Test 18, Beam 10, End B, 2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 126 Inch Embedment Length.)

Table 3-1. Outline of Flexural Tests Performed.			
TEST #	BEAM #, END {STRAND SPACING (in.), MIX, CONFINEMENT}	SPAN TESTED (ft.)	EMBEDMENT LENGTH (in.)
1	2, A {1.75,NS,UC}	21	96
2	1, A {1.75,NS,UC}	21	114
3	3, B {1.75,NS,UC}	25	126
4	3, A {1.75,NS,UC}	25	150
5	6, A {1.75,NS,UC}	28	168
6	6, B {1.75,NS,UC}	30	180
7	4, B {1.75,HS,UC}	25	126
8	5, A {1.75,HS,UC}	25	150
9	7, A {2.0,NS,UC}	21	96
10	8, A {2.0,NS,UC}	21	114
11	9, A {2.0,NS,UC}	25	126
12	9, B {2.0,NS,UC}	25	150
13	12, B {2.0,NS,UC}	25	150
14	12, A {2.0,NS,UC}	28	168
15	10, A {2.0,HS,UC}	25	108
16	11, B {2.0,HS,UC}	25	108
17	11, A {2.0,HS,UC}	25	126
18	10, B {2.0,HS,UC}	25	126
20	13, B {1.75,NS,C}	21	114
21	13, A {1.75,NS,C}	25	126
22	14, B {2.0,NS,C}	21	114
23	14, A {2.0,NS,C}	25	126

Notes: Mix: NS - Normal Strength
HS - High Strength
Confinement: UC - Unconfined C - Confined

No data for test 19 due to problems with the data acquisition unit.

CHAPTER 4

4. TEST RESULTS

4.1 Transfer Length

The results of the transfer length measurements are shown in Table 4-1 for specimens with 1.75 inch strand spacing and Table 4-2 for specimens with 2.0 inch strand spacing. The transfer lengths reported are estimated from plots of the surface strain measurements taken immediately after transfer. These plots can be found in Appendix B with the estimated strain plateau and estimated transfer length marked. For this study the transfer length was defined as the embedment length of strand necessary to transfer one-hundred percent of the effective prestress to the concrete immediately after release. This method is one of three for determining transfer length from concrete surface strain measurements reported in the "Previous Studies" section in Chapter 1 of this paper. The other two methods are the slope-intercept method [4] and the ninety-five percent method [3]. Using the embedment length required to transfer one-hundred percent of the effective prestress immediately

Table 4-1. Transfer Length Results For Specimens With 1.75 Inch Strand Spacing.

BEAM NUMBER {POUR NUMBER, CONCRETE MIX, CONFINEMENT}	f'_{ci} (psi)	f_{si} (ksi) $\{f_{si}/f_{pu}\}$	ESTIMATED STRAIN PLATEAU END A/END B ($\mu\epsilon$)	MEASURED TRANSFER LENGTH END A/END B (in.)	ACI TRANSFER LENGTH (in.)
1 {1,NS,UC}	5310	202 {0.748}	370/375	58/58	26
2 {1,NS,UC}	5310	202 {0.748}	300/300	68/68	26
3 {2,NS,UC}	5350	205 {0.759}	327/429	41/45	27
4 {3,HS,UC}	8220	207 {0.767}	311/450	37/32	28
5 {4,HS,UC}	7690	209 {0.774}	363/NA	49/NA	28
6 {5,NS,UC}	7660	210 {0.778}	373/356	40/37	27
13 {6,NS,C}	6010	209 {0.774}	366/372	41/36	27
Averages		206 {0.763)	361	47	27

Notes: CONCRETE MIX: NS = normal strength mix HS = high strength mix
CONFINEMENT: UC = unconfined C = confined

f'_{ci} = compressive strength of concrete at transfer
f_{si} = stress in strand immediately after transfer
f_{pu} = 270 ksi
NA = no data available

ACI transfer length based on f_{se} in Tables 4-5, 4-6, and 4-7.

Table 4-2. Transfer Length Results For Specimens With 2.0 Inch Strand Spacing.

BEAM NUMBER {POUR NUMBER, CONCRETE MIX, CONFINEMENT}	f'_{ci} (psi)	f_{si} (ksi) {f_{si}/f_{pu}}	ESTIMATED STRAIN PLATEAU END A/END B ($\mu\epsilon$)	MEASURED TRANSFER LENGTH END A/END B (in.)	ACI TRANSFER LENGTH (in.)
7 {1,NS,UC}	5310	203 {0.752}	310/309	64/48	26
8 {1,NS,UC}	5310	203 {0.752}	273/393	63/54	26
9 {2,NS,UC}	5350	208 {0.770}	354/359	52/54	27
10 {3,HS,UC}	8220	209 {0.774}	327/313	26/34	28
11 {4,HS,UC}	7690	208 {0.770}	365/352	41/43	28
12 {5,NS,UC}	7660	210 {0.778}	347/316	41/27	28
14 {6,NS,C}	6010	208 {0.770}	286/353	35/30	28
Averages		207 {0.767}	333	44	27

Notes: CONCRETE MIX: NS = normal strength mix HS = high strength mix
CONFINEMENT: UC = unconfined C = confined

f'_{ci} = compressive concrete strength at transfer
f_{si} = stress in strand immediately after transfer
f_{pu} = 270 ksi

ACI transfer length based on f_{se} in Tables 4-5, 4-6, and 4-7.

after release results in the longest transfer lengths of the three methods.

A sample plot of concrete surface strain measurements for end B of beam 14 is shown in Figure 4-1. The X's show points dropped by a statistical approach discussed in Chapter 3. The fully reduced concrete surface strain plots for each end of each beam immediately after transfer can be found in Appendix B. Complete raw data plots of concrete surface strain for each end of each beam at time intervals after transfer can be found in Appendix A. The horizontal dashed line in Figure 4-1 is the final average strain plateau (353 microstrains), and the vertical dashed line is the final estimation of the transfer length (30 inches).

Table 4-1 lists the seven specimens with a strand spacing of 1.75 inches, and Table 4-2 lists the seven specimens with a strand spacing of 2.0 inches. Noting that each strand spacing had an equal number of normal strength mix, high strength mix, unconfined, and confined specimens, the averages shown in Tables 4-1 and 4-2 shows only the effect of strand spacing on transfer length. The average transfer lengths for all specimens as shown in Tables 4-1 and 4-2 were 47 inches and 44 inches for the 1.75 inch and 2.0 inch strand spacings, respectively. The difference in the average transfer lengths for the two strand spacings cannot easily be contributed to the difference in strand spacing for the following reason. The gage length for the

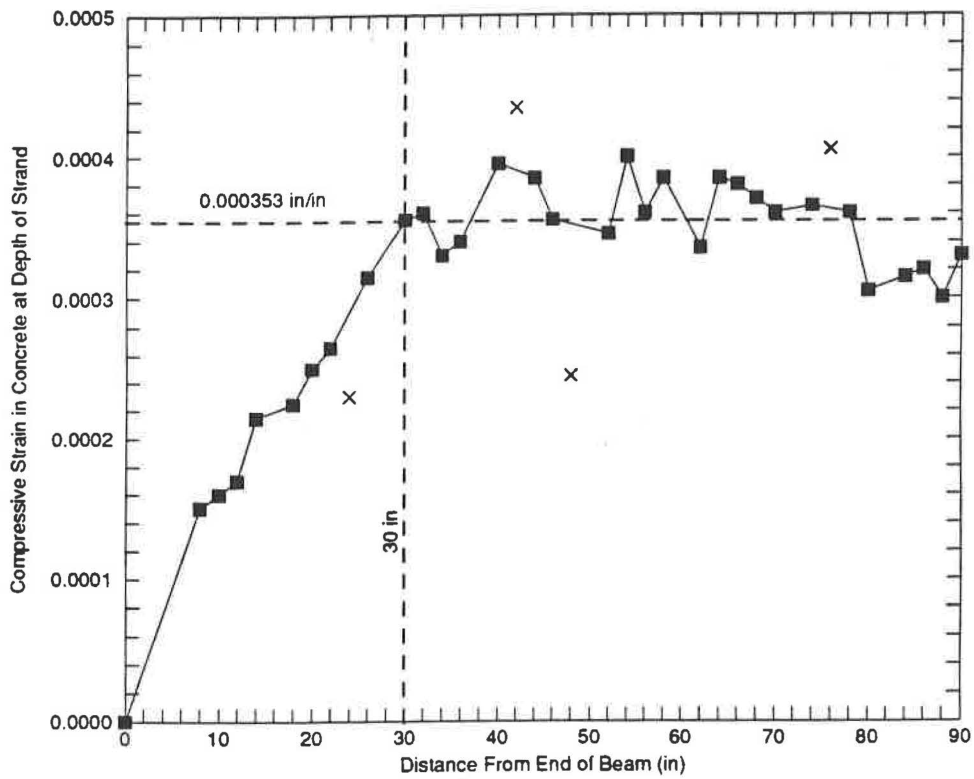


Figure 4-1. Typical Reduced Surface Strain Measurements Immediately After Transfer Showing the Average Strain Plateau and Transfer Length. (Beam 14, End B, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

surface strain measurements was 10.0 inches, and the average strain for the 10.0 inch gage length was defined as the strain for an element at the midpoint of the gage length. The threaded inserts were on 2.0 inch centers. Although use of a 10.0 inch gage length gave a good estimate of the transfer length, the accuracy of the estimates was at best plus or minus 2.0 inches due to the spacing of the threaded inserts. Therefore, it was not shown that the difference in the strand spacings had a measurable effect on the transfer lengths of the specimens.

The level of effective concrete strain in each specimen (estimated strain plateau in Tables 4-1 and 4-2) illustrates another important result of the transfer length measurements. The effective prestress was fully transferred to the beams with the closer strand spacing of 1.75 inches. The effective concrete strain immediately after transfer for all specimens was calculated to be an average of 270 microstrains which is less than the estimated strain plateau values from Tables 4-1 and 4-2. The difference between measured and calculated concrete surface strains was due to creep and shrinkage in the first four to six hours after release while measurements were being made. Also, it is important to note that there was no cracking of any specimens at transfer of prestressing force.

Noting that the strand spacing had little effect on the transfer length, Tables 4-1 and 4-2 were rearranged to form

Table 4-3 to show the effects of concrete strength and confinement on transfer length. An interesting result was seen when the specimens were arranged into three categories:

1) unconfined specimens of normal strength mix,
2) unconfined specimens of high strength mix, and
3) confined specimens of normal strength mix.

As shown in Table 4-3 the average transfer length of the unconfined specimens of normal strength mix was 51 inches with a standard deviation of 11.6 inches. Due to the poor and erratic results of beams 1, 2, 7, and 8 from the first pour as shown in Appendix A, an estimated transfer length was difficult to define. Eliminating the above beams from Table 4-3 produced an average transfer length of 42 inches and a standard deviation of 8.0 inches for the unconfined specimens of normal strength mix. Eliminating these four beams obviously improved the average transfer length, but more importantly it improved the standard deviation of the remaining data, suggesting that these transfer lengths were not representative of the set. The average transfer length of unconfined specimens of high strength mix was 37 inches, and the average transfer length of confined specimens of normal strength mix was 36 inches. The evident decrease of transfer length from 42 inches to 36 and 37 inches suggests that increasing concrete strength and/or adding confining steel decreases the transfer length of a specimen.

Table 4-3. Transfer Length Results With Respect to Concrete Strength and Confinement.

BEAM NUMBER	ESTIMATED TRANSFER LENGTH (in.) END A/END B		
	NS MIX, UNCONFINED	HS MIX, UNCONFINED	NS MIX, CONFINED
1	58/58		
2	68/68		
3	41/45		
4		37/32	
5		49/NA	
6	40/37		
7	64/48		
8	63/54		
9	52/54		
10		26/34	
11		41/43	
12	41/27		
13			41/36
14			35/30
Average {Std Dev}	51 {11.6}	37 {7.1}	36 {3.9}

Notes: NS = normal strength mix
HS = high strength
NA = no data available
Std Dev = standard deviation

The magnitude of the transfer lengths reported herein are somewhat larger than that given by the ACI recommendations. The portion of the ACI equation for development length (ACI 12.9.1) [1] which accounts for transfer length is:

$$L_t = \frac{f_{se}}{3} d_b \qquad \textit{Eq. } 4\text{-}1$$

where: L_t = transfer length
f_{se} = effective prestress (after all prestress losses)
d_b = nominal strand diameter

The last column in Tables 4-1 and 4-2 shows the transfer lengths for the specimens as calculated by Equation 4-1. The f_{se} value used in the calculation of Equation 4-1 is found in Tables 4-5, 4-6, and 4-7. The f_{se} value in those tables was the calculated long-term effective strand stress based on prestress losses over a five year period. The average measured transfer length of all specimens reported in Tables 4-1 and 4-2 excluding pour 1 (beams 1, 2, 7, and 8) was 39 inches, however, the average transfer length calculated by Equation 4-1 was 27 inches. The average measured transfer length was approximately forty-five percent higher than that calculated by Equation 4-1. Table 4-4 gives a summary of the transfer length results.

Table 4-4. Summary of Transfer Length Results.

SPECIMEN DESCRIPTION	TRANSFER LENGTH (in.)
Unconfined, Normal Strength Mix	42
Unconfined, High Strength Mix	37
Confined, Normal Strength Mix	36

Notes:
1) No discernible difference in transfer length caused by the two strand spacings of 1.75 inches and 2.0 inches.
2) Increasing concrete strength decreases transfer length.
3) Adding confining steel around the strands of the specimen decreases transfer length.

4.2 Development Length and Nominal Moment Capacity

Tables 4-5, 4-6, and 4-7 contain flexural test results for unconfined specimens of 1.75 inch strand spacing, unconfined specimens of 2.0 inch strand spacing, and confined specimens of 1.75 and 2.0 inch strand spacings, respectively. The tables include the development length and nominal moment capacity of the specimens as calculated by the appropriate ACI equations (ACI 12.9.1, ACI 18.7.1) [1]. The tables also include the embedment length and the type of failure for each test. Tables 4-5 and 4-6 are divided into two sections: specimens of normal strength mix, and specimens of high strength mix. Table 4-7 is divided into two sections according to strand spacing. All three tables list the tests in order of ascending embedment lengths for the particular category of beam. The beams were divided into six categories in order to study the effects of strand spacing, concrete strength, and confinement on development length. The six categories of beams included the following:

1) unconfined specimens of normal strength mix with 1.75 inch strand spacing,
2) unconfined specimens of high strength mix with 1.75 inch strand spacing,
3) unconfined specimens of normal strength mix with 2.0 inch strand spacing,
4) unconfined specimens of high strength mix with 2.0 inch strand spacing,

Table 4-5. Flexural Test Results for Unconfined Specimens With 1.75 Inch Strand Spacing.

TEST # {BEAM #, END}	f'_c (psi)	f_{se} (ksi)	f_{ps} (ksi) ACI/STRAIN COMPAT.	EMBEDMENT LENGTH (in.)	ACI DEVELOP. LENGTH (in.)	$M_{fail}/M_{n,ACI}$ (in-kips)	TYPE OF FAILURE
a) Specimens of Normal Strength Mix							
1 {2,A}	6310	153	245/274	96	72	0.54 {1940/3580}	B
2 {1,A}	6310	153	245/270	114	72	0.66 {2370/3580}	B
3 {3,B}	6460	160	245/274	126	69	1.04 {3760/3610}	F/S
4 {3,A}	7430	160	247/277	150	69	1.03 {3810/3690}	F/S
5 {6,A}	8010	164	248/280	168	69	1.07 {3990/3740}	F/S
6 {6,B}	7930	164	248/280	180	69	1.09 {4080/3740}	F/S
b) Specimens of High Strength Mix							
7 {4,B}	11000	165	254/280	126	70	1.01 {3970/3940}	F/S
8 {5,A}	10070	166	253/280	150	70	1.04 {4040/3890}	F

Notes: f'_c is at the time of test.
f_{se} is the long-term effective stress in the strand based on five years of estimated losses.
TYPE OF FAILURE: B = Bond F = Flexure F/S = Flex/Slip

Table 4-6. Flexural Test Results for Unconfined Specimens With 2.0 Inch Strand Spacing.

TEST # {BEAM #, END}	f'_c (psi)	f_{se} (ksi)	f_{ps} (ksi) ACI/STRAIN COMPAT.	EMBEDMENT LENGTH (in.)	ACI DEVELOP. LENGTH (in.)	$M_{fail}/M_{n,ACI}$ (in-kips)	TYPE OF FAILURE
a) Specimens of Normal Strength Mix							
9 {7,A}	6310	155	245/271	96	71	0.59 {2140/3600}	B
10 {8,A}	6310	155	245/271	114	71	0.69 {2470/3600}	B
11 {9,A}	6460	163	245/275	126	68	1.03 {3750/3630}	F/S
12 {9,B}	7430	163	247/278	150	69	1.01 {3760/3710}	F/S
13 {12,A}	7930	165	248/280	150	69	1.10 {4130/3750}	F/S
14 {12,B}	8010	165	248/280	168	69	1.08 {4040/3750}	F
b) Specimens of High Strength Mix							
15 {10,A}	11620	168	255/280	108	69	1.07 {4260/3990}	F/S
16 {11,B}	10490	166	253/280	108	69	1.04 {4100/3930}	F
17 {11,A}	10070	166	253/280	126	69	1.08 {4220/3910}	F/S
18 {10,B}	11000	168	254/280	126	69	1.05 {4150/3960}	F

Notes: f'_c is at the time of test.
f_{se} is the long-term effective stress in the strand based on five years of estimated losses.
TYPE OF FAILURE: B = Bond F = Flexure F/S = Flex/Slip

Table 4-7. Flexural Test Results for Confined Specimens.							
TEST # {BEAM #, END}	f'_c (psi)	f_{se} (ksi)	f_{ps} (ksi) ACI/STRAIN COMPAT.	EMBEDMENT LENGTH (in.)	ACI DEVELOP. LENGTH (in.)	$M_{fail}/M_{n,ACI}$ (in-kips)	TYPE OF FAILURE
a) Specimens With 1.75 Inch Strand Spacing.							
20 {13,B}	7990	162	247/279	114	70	1.11 {4160/3740}	F/S
21 {13,A}	7990	162	247/279	126	70	1.07 {3990/3740}	F/S
b) Specimens With 2.0 Inch Strand Spacing.							
22 {14,B}	8220	165	249/280	114	70	1.08 {4070/3770}	F/S
23 {14,A}	7760	165	248/279	126	69	1.15 {4280/3740}	F/S

Notes: f'_c is at the time of test.
f_{se} is the long-term effective stress in the strand based on five years of estimated losses.
TYPE OF FAILURE: B = Bond F = Flexure F/S = Flex/Slip

5) confined specimens of normal strength mix with 1.75 inch strand spacing, and

6) confined specimens of normal strength mix with 2.0 inch strand spacing.

The stress in the strand at the nominal moment capacity, f_{ps}, is shown for each specimen in Tables 4-5, 4-6, and 4-7. It was desired that the cross-section be under-reinforced, and, therefore that f_{ps} be greater than the yield stress of the strand (263 ksi) reported by the manufacturer. Two methods which gave significantly different results were used for calculating f_{ps}: equation 18-3 from ACI 318-89 [1] and the strain compatibility method. ACI equation 18-3 is an empirical equation based on average results for typical stress versus strain curves for prestressing strand. For the calculations performed with the ACI equation, 270 ksi was used as f_{pu} to give an ACI design value for f_{ps}. Because the actual stress versus strain behavior of strand can be used in the strain compatibility method, that method is considered to be more representative of the actual behavior of a prestressed beam. The stress-strain plot supplied by the manufacturer of the strand was used in the strain compatibility calculations for each test specimen. The f_{ps} values from the strain compatibility calculations are shown in Tables 4-5, 4-6, and 4-7. The f_{ps} values from strain compatibility calculations are about twelve percent larger than those obtained from ACI equation 18-3. These values of f_{ps} illustrate the differences between the design standards and actual strand data. The results of the strain compatibility method indicate that an under-reinforced section was achieved. In the calculations of ACI development length and nominal moment capacity, $M_{n,ACI}$, in Tables 4-5, 4-6 and 4-7, the f_{ps} obtained from ACI equation 18-3 was used.

4.2.1 Deformation Behavior. Three types of failures were observed during the testing: bond failure, flex/slip failure, and flexural failure. The end slip measurements and maximum applied moments at the critical section were used to determine the failure mode of a given test. Bond failure was characterized by significant slip of all strands and an inability to achieve the calculated nominal moment capacity of the section. Bond failures also exhibited flexural cracking very near the end of the transfer length. Flex/slip failure was characterized by crushing of the top concrete fibers at the nominal moment capacity with an end slip of at least 0.01 inches in one or more of the strands. Flexural failure was characterized by crushing of the top concrete fibers at the nominal moment capacity without measurable end slip of any strand. Typical plots of moment versus end slip and moment versus deflection for the three types of failure can be found in Chapter 3 in Figures 3-2, 3-3, and 3-4. Plots for all twenty-three flexural tests can be found in Appendix C. Appendix D contains the crack profiles of each flexural test.

4.2.2 Discussion of Results: Unconfined, Normal Strength Concrete. The first two tests for each strand spacing with unconfined normal strength mix (tests 1, 2, 9, and 10) were performed at 96 inches and 114 inches. These four tests resulted in bond failures characterized by large end slips and flexural cracking at the end of the transfer length. Also, the applied moment at the critical section ranged from fifty-four to sixty-nine percent of the calculated nominal moment capacity of the section, $M_{n,ACI}$.

Subsequently, the embedment lengths for the unconfined specimens of normal concrete mix were increased in approximately one to two foot increments for tests 3 through 6 for the 1.75 inch strand spacing and tests 11 through 14 for the 2.0 inch strand spacing. These tests are listed as flexure or flex/slip failures in the tables. The applied moments at the critical section at failure for these tests averaged six percent larger than the calculated nominal moment capacity, and in each test failure was due to concrete crushing at the point of load accompanied by significant tensile cracking of the concrete.

The insignificance of the effect of the two strand spacings on moment capacity can be seen by comparing companion tests as shown in Table 4-8. For example a comparison of test 3 (an unconfined, normal strength

Table 4-8. Comparison of Tests at Same Embedment Length With Different Strand Spacings.

EMBEDMENT LENGTH (in.)	1.75 INCH STRAND SPACING			2.0 INCH STRAND SPACING		
	TEST #	RATIO OF $M_{fail}/M_{n,ACI}$	TYPE OF FAILURE	TEST #	RATIO OF $M_{fail}/M_{n,ACI}$	TYPE OF FAILURE
a) Unconfined Specimens of Normal Strength Mix						
96	1	0.54	Bond	9	0.59	Bond
114	2	0.66	Bond	10	0.69	Bond
126	3	1.04	Flex/Slip	11	1.03	Flex/Slip
150	4	1.03	Flex/Slip	12	1.01	Flex/Slip
				13	1.10	Flex/Slip
168	5	1.07	Flex/Slip	14	1.08	Flexure
b) Unconfined Specimens of High Strength Mix						
126	7	1.01	Flex/Slip	17	1.08	Flex/Slip
				18	1.05	Flexure

Notes: M_{fail} = maximum moment at critical section at time of failure
$M_{n,ACI}$ = ACI nominal moment capacity

specimen with 1.75 inch strand spacing at an embedment length of 126 inches) with test 11 (an unconfined, normal strength specimen with 2.0 inch strand spacing at an embedment length of 126 inches) shows virtually identical behavior with no significant difference in moment capacity between the two tests with different strand spacings.

For the unconfined specimens with normal strength mix, the longest embedment length that resulted in a bond failure was 114 inches, and the shortest embedment length that resulted in a flexure or flex/slip failure was 126 inches. Therefore, the development length of these unconfined, normal strength specimens was between 114 inches and 126 inches for both strand spacings.

4.2.3 Discussion of Results: Confined, Normal Strength Concrete. From Table 4-7 it can be seen that the introduction of confinement steel had an effect on the development length of the normal strength mix specimens. Tests were performed at an embedment length of 114 inches for each strand spacing, and the failure mode was flex/slip. The development length of the confined, normal strength mix specimens was, therefore, less than 114 inches. This indicates a reduction in the development length due to the confinement steel since all the tests on unconfined specimens tested at an embedment length of 114 inches exhibited bond failures. A range cannot be established for the development length of confined, normal strength mix specimens because testing of confined specimens did not include a bond failure, but it can be seen that the development length was shortened.

4.2.4 Discussion of Results: Unconfined, High Strength Concrete. A total of six flexural tests were conducted on specimens made with the high strength concrete mix. As shown in the bottom sections of Tables 4-5 and 4-6, none of these tests resulted in a bond failure. Nominal moment capacity does not appear to be affected by the two different strand spacings. Each of the tests of specimens of high strength mix had a tested moment capacity greater than the nominal moment capacity given by the ACI equations.

Although there were not enough tests performed of specimens made with high strength concrete to predict a development length, some general conclusions about development length can be made. The development length of the high strength concrete specimens was less than that for the normal strength concrete specimens. Based on tests 15 and 16 the development length for the unconfined specimens of high strength concrete was less than 108 inches. An embedment length shorter than 108 inches was not performed, therefore, an embedment length test resulting in a bond failure was not found. However, a development length less than 108 inches was less than the range of 114 inches to 126 inches reported for the unconfined specimens of normal strength mix. A decrease in development length as a result

Table 4-9. Summary of Development Length Results.

SPECIMEN DESCRIPTION	DEVELOPMENT LENGTH SUMMARY
Unconfined, Normal Strength Mix	Between 114 Inches And 126 Inches
Unconfined, High Strength Mix	Unknown, But Less Than 108 Inches
Confined, Normal Strength Mix	Unknown, But Less Than 114 Inches

Notes:

1) No discernible difference in development length caused by the two strand spacings of 1.75 inches and 2.0 inches.
2) Increasing concrete strength decreases development length.
3) Adding confining steel around the strands of the specimen decreases development length.

of increased concrete strength was evident. Table 4-9 contains a summary of the effects of strand spacing, concrete strength, and confinement on development length.

4.3 Comparison of Results to Other Research

The results found in the literature and reported in the "Previous Studies" section of Chapter 1 of this paper are comparable to the results of the research reported herein. Two of the studies (Texas, Florida) considered specimens with 0.6 inch diameter strand spaced at 2.0 inches, and the other study (Tennessee) and the one herein investigated 0.5 inch diameter strand at a 1.75 inch strand spacing. Both of these spacings are less than the ACI recommendations.

In the three previous studies and in the tests reported here, no cracking of prestressed specimens at transfer due to insufficient spacing was reported. Average transfer lengths ranged from a low of 30 inches (Florida) to a high of 39 inches (this report). The transfer lengths reported in this paper were on average about 5 inches longer than those reported by other researchers. Some of this difference can be accounted for in the different methods used for estimating transfer length. The most conservative, hence the one that yields the longest transfer lengths, was used in the study reported herein. Another explanation for the differences in measured transfer lengths between studies is variations in the surface condition of the strand due to different manufacturing techniques and storage methods. The fact that other researchers measured shorter transfer lengths and still did not experience any cracking at transfer only serves to strengthen the argument for allowing decreased strand spacings. A shorter transfer length would introduce larger circumferential (splitting) stresses into the transfer zone, and, therefore, increase the probability of cracking at transfer.

Two of the three studies reported in the Previous Studies section of Chapter 1 of this paper conducted flexural tests of prestressed beam specimens with strand spacings less than required by ACI. One study (Texas) tested specimens with 0.6 inch diameter strand at a spacing of 2 inches, and the other (Tennessee) tested specimens with 0.5 inch diameter strand spaced at 1.75 inches. Both studies reported no reduction in nominal moment capacity or increase in development length due to decreased strand spacing. Similarly, in the research reported herein, no reduction in performance of prestressed beam specimens was observed with the decreased strand spacing.

The study conducted at The University of Texas at Austin reported development lengths very close to those predicted by the ACI equation, while the study conducted by The University of Tennessee at Knoxville reported measured development lengths on the order of twenty percent greater than those predicted by the ACI equation. Development lengths reported herein for unconfined specimens of normal strength mix were about sixty-nine percent longer than those predicted by the ACI equation (120 inches versus 71 inches). For confined specimens of normal strength mix, the development lengths reported herein were somewhere less than sixty percent longer than those predicted by the ACI equation (less than 114 inches versus 71 inches). For unconfined specimens of high strength mix, the development lengths reported herein were somewhere less than fifty-two percent longer the those predicted by the ACI equation (less than 108 inches versus 71 inches).

Differences in the development lengths reported by the researchers can be explained. As has already been suggested, variations in the surface condition of the strand affects strand bond to concrete. Also, the mode of failure observed in this study could have affected the magnitude of the development length. The bond failures that were seen in four tests were accompanied by flexural cracking near the end of the transfer length. The cracking moment of the cross-section was exceeded near the end of the measured transfer length well before the critical section reached its nominal moment capacity. If the transfer length for the specimens was shorter or the ratio of cracking moment to nominal moment capacity were larger, the development length might be shorter.

CHAPTER 5

5. CONCLUSIONS

Based on an analysis of the experimental results, the following conclusions for specimens prestressed with 0.5 inch diameter strand can be drawn:

1. Decreasing the strand spacing in pretensioned, prestressed members from 2.0 inches to 1.75 inches has no significant effect on transfer length and does not result in splitting of members at transfer of prestressing force.

2. Decreasing the strand spacing in pretensioned, prestressed members from 2.0 inches to 1.75 inches has no significant effect on development length or nominal moment capacity.

3. Increasing the concrete strength from a normal strength mix (6,000 to 8,000 psi) to a

high strength mix (10,000 to 12,000 psi) reduces the transfer length and development length.

4. Enclosing the strand pattern with confining steel reduces the transfer length and development length.

No testing of specimens with 0.6 inch strand was conducted as part of this research project. Based on the results of other researchers [3,4,5] and the results reported herein for specimens prestressed with 0.5 inch diameter strand, the use of 0.6 inch diameter strand at a spacing of 2.0 inches does appear reasonable.

The ratio of cracking moment to nominal moment capacity appears to be an important variable in the measurement of development length that has not been studied yet. It would seem that decreasing the ratio of cracking moment to nominal moment capacity would increase the chance of cracking near the transfer zone creating larger strand stresses in this region. The smaller ratio would then increase development length.

REFERENCES

1 - ACI Committee 318, Building Code Requirements for Reinforced Concrete (ACI 318-89), American Concrete Institute, Detroit, MI, 1989.

2 - AASHTO, Standard Specifications for Highway Bridges, American Association of State Highway and Transportation Officials, Washington, D.C., 1983.

3 - Russell, B. W., Design Guidelines for Transfer, Development and Debonding of Large Diameter Seven Wire Strands in Pretensioned Concrete Girders, Dissertation, The University of Texas at Austin, December, 1992.

4 - Deatherage, J. H., and Burdette, E. G., Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Products, Final Report, The University of Tennessee, Knoxville, Transportation Center, September, 1991.

5 - Shahawy, M. A., Issa, M., and deV Batchelor, B., "Strand Transfer Lengths in Full Scale AASHTO Prestressed Concrete Girders," PCI Journal, Vol. 37, No. 3, May/June, 1992, pp. 84-96.

6 - ASTM, "Uncoated Seven-Wire Stress-Relieved Steel Strand for Prestressed Concrete, Supplement for Low-Relaxation Strand," ASTM A-416-90A, American Society for Testing and Materials, Philadelphia, PA, 1990.

7 - Cousins, T. C., Johnston, D. W., and Zia, P., "Transfer Length of Epoxy Coated Prestressing Strand," ACI Materials Journal, Vol. 87, No. 3, May/June, 1990, pp. 193-203.

8 - Nanni, A., Utsunomiya, T., Yonekura, H., and Tanigaki, M., "Transmission of Prestressing Force to Concrete by Bonded Fiber Reinforced Plastic Tendons," ACI Structural Journal, Vol. 89, No. 3, May/June, 1992, pp. 335-344.

9 - Francis, L. H., Spacing and Concrete Cover Requirements for Epoxy Coated Prestressing Strand, Thesis, Auburn University, August 1992.

10 - Nawy, E. G., Prestressed Concrete: A Fundamental Approach, Prentice-Hall, Englewood Cliffs, N. J., 1989.

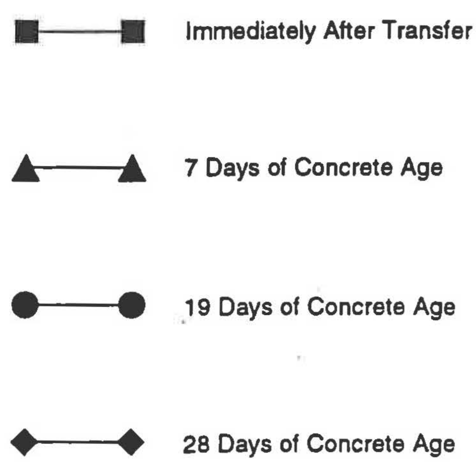
APPENDIX A

A. RAW SURFACE STRAIN PLOTS AT TIME INTERVALS

The surface strain plots in Appendix A include all raw measurements made for each end of each beam as described in Chapter 3. The surface strains were measured immediately after transfer for all beams. For most beams the surface strains were also measured at some time interval after transfer. The graphs show the actual measurements taken. It was a concern that the strain due to the self-weight moment of the beam (due to the simple support condition caused by camber) could affect the strain measurements. The self-weight strain at the effective depth of strand was investigated and found to be at least an order of magnitude smaller than the prestressing strain. The plots in Appendix A include all raw data taken before the "bad points" were dropped through the statistical analysis described in Chapter 3.

Each figure number coincides with the beam number on which the surface strain measurements were taken. Each figure includes the surface strain measurements for each end of a given beam. The top plot in each figure is the surface strain versus distance from the end of the beam for end A. The bottom plot in each figure is the surface strain versus distance from the end of the beam for end B. The figure titles include the important information about each beam: strand spacing, pour number and concrete strength category, and confinement information.

The following legend shows the symbols corresponding to the concrete age at which surface strain measurements were taken. This legend applies to all figures in Appendix A.



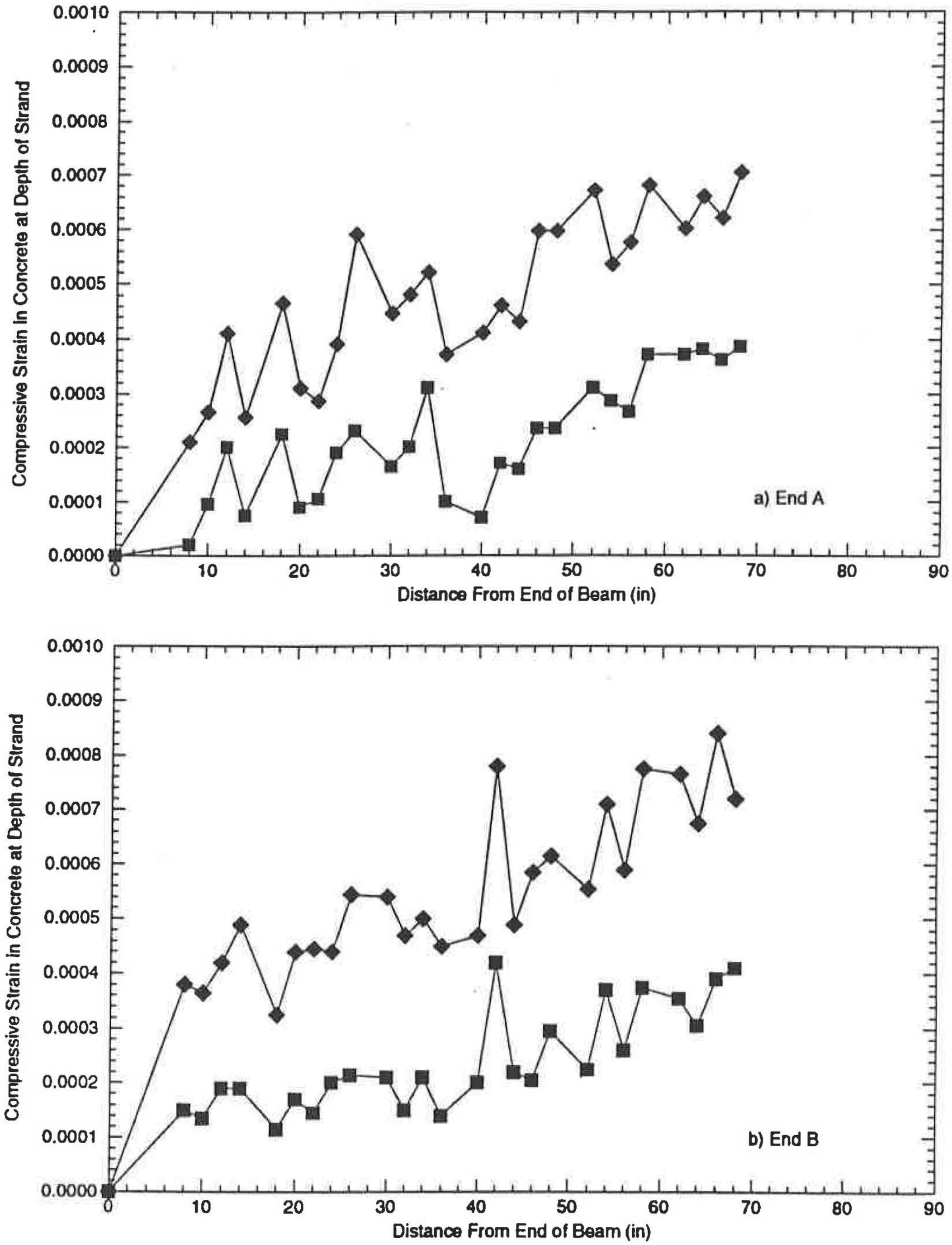


Figure A-1. All Raw Surface Strain Measurements Taken for Each End of Beam 1. (1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

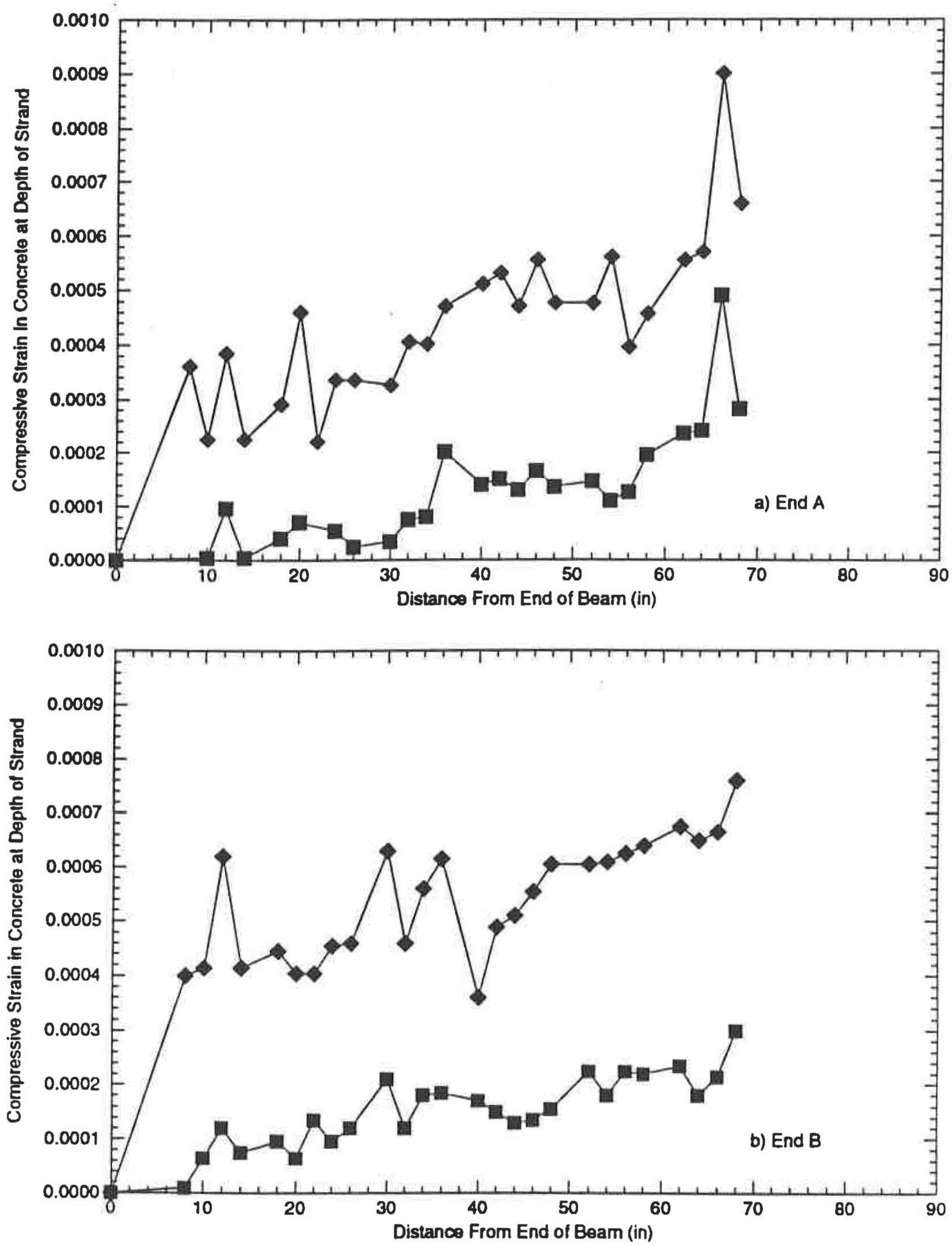


Figure A-2. All Raw Surface Strain Measurements Taken for Each End of Beam 2. (1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

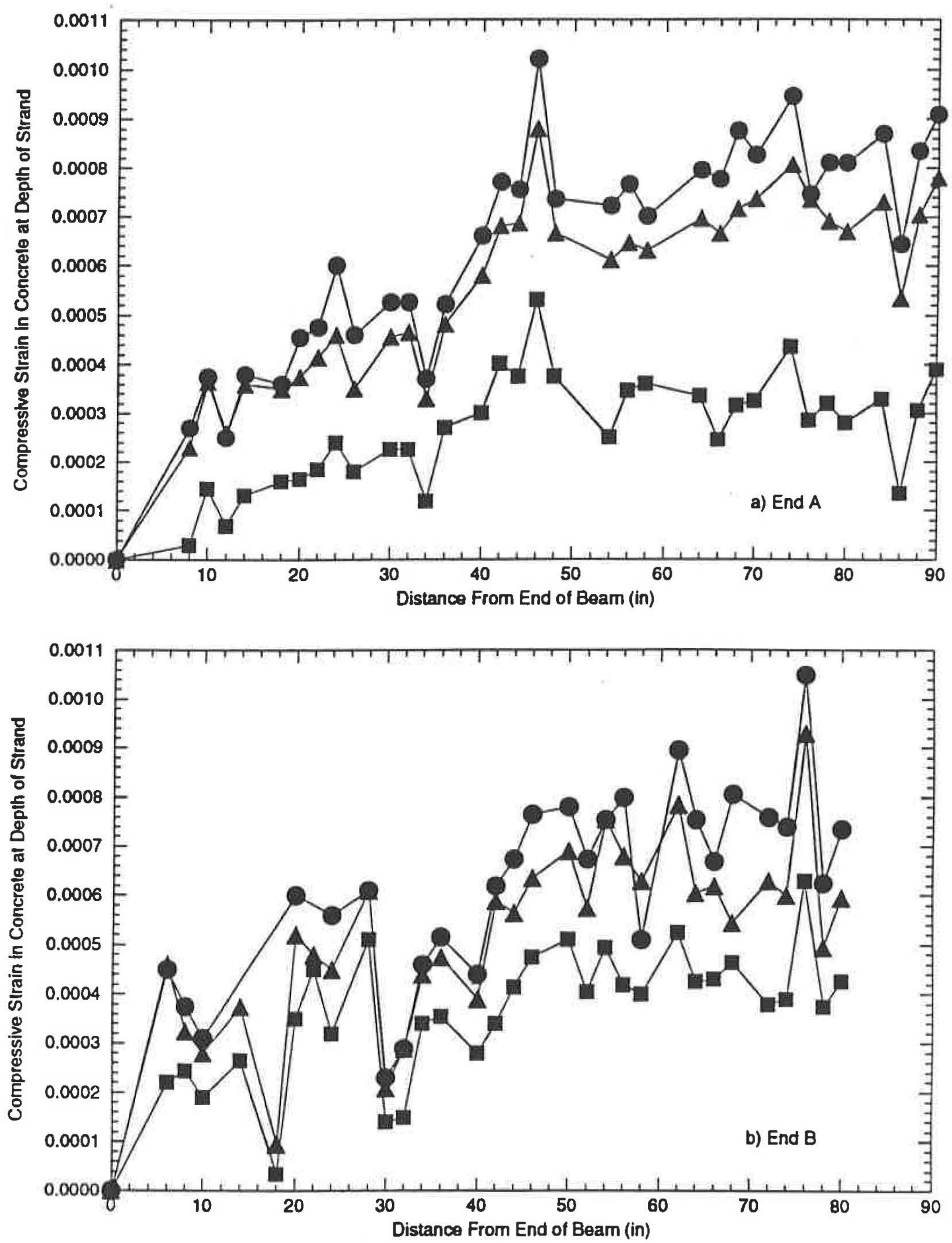


Figure A-3. All Raw Surface Strain Measurements Taken for Each End of Beam 3. (1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined.)

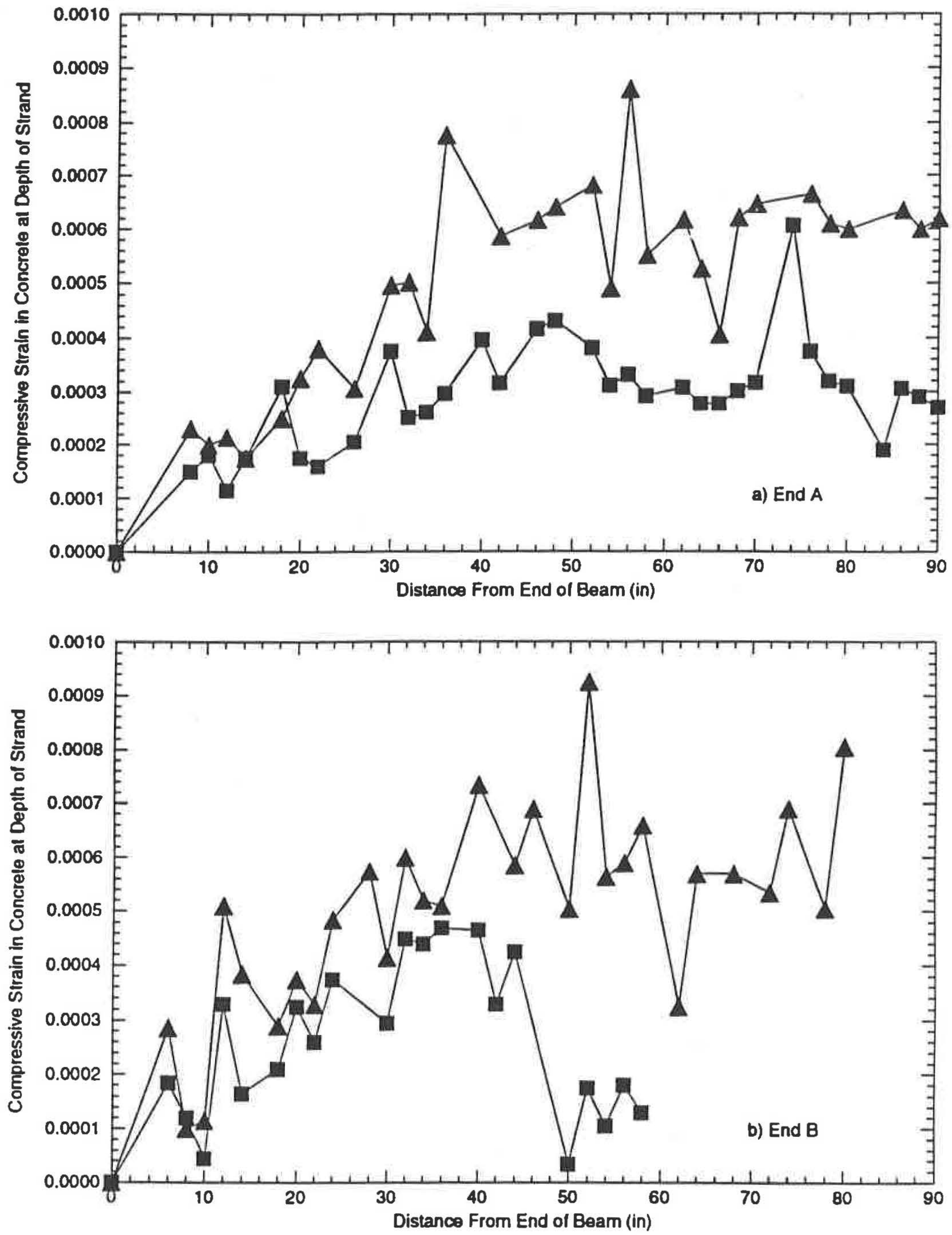


Figure A-4. All Raw Surface Strain Measurements Taken for Each End of Beam 4. (1.75 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined.)

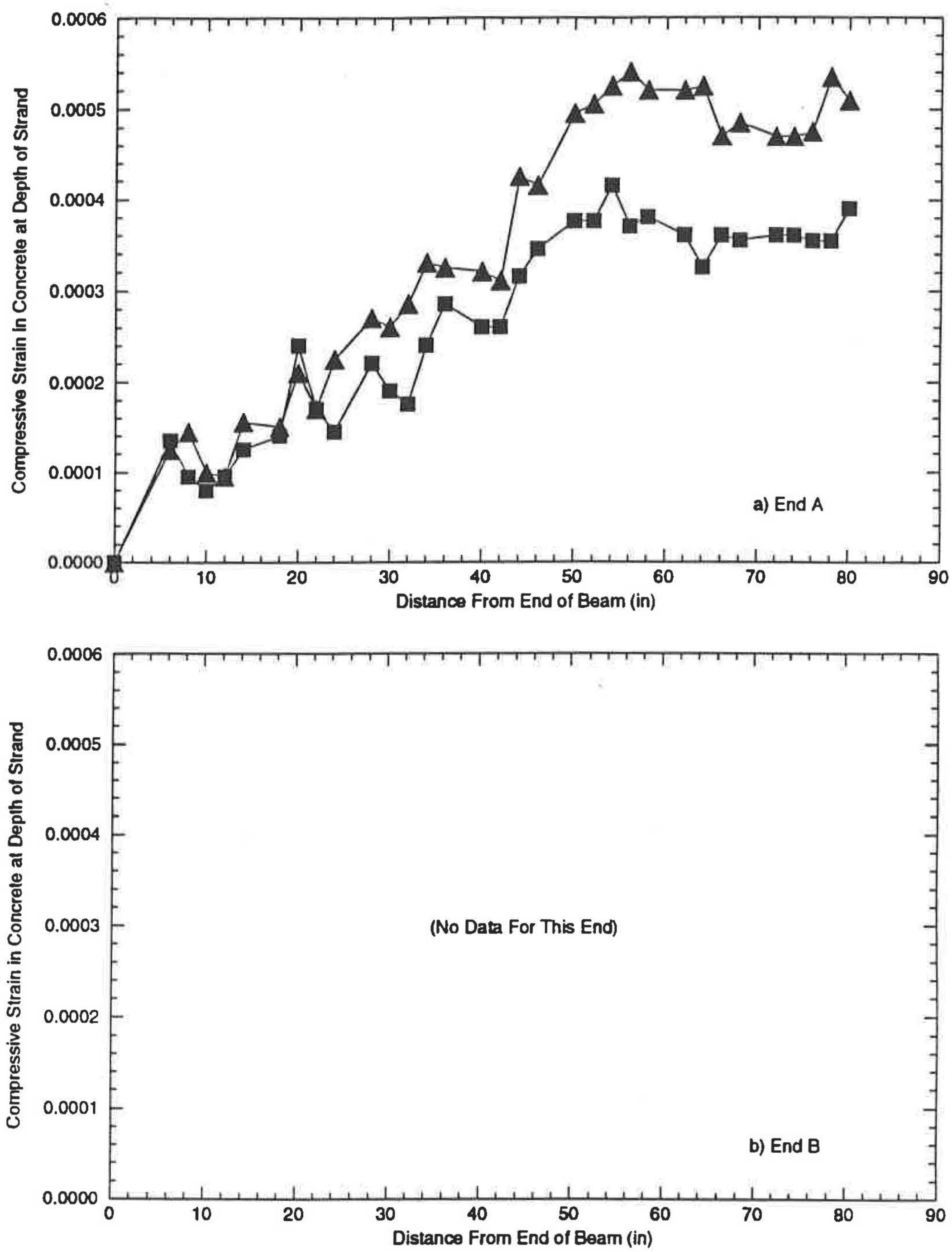


Figure A-5. All Raw Surface Strain Measurements Taken for Each End of Beam 5. (1.75 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined.)

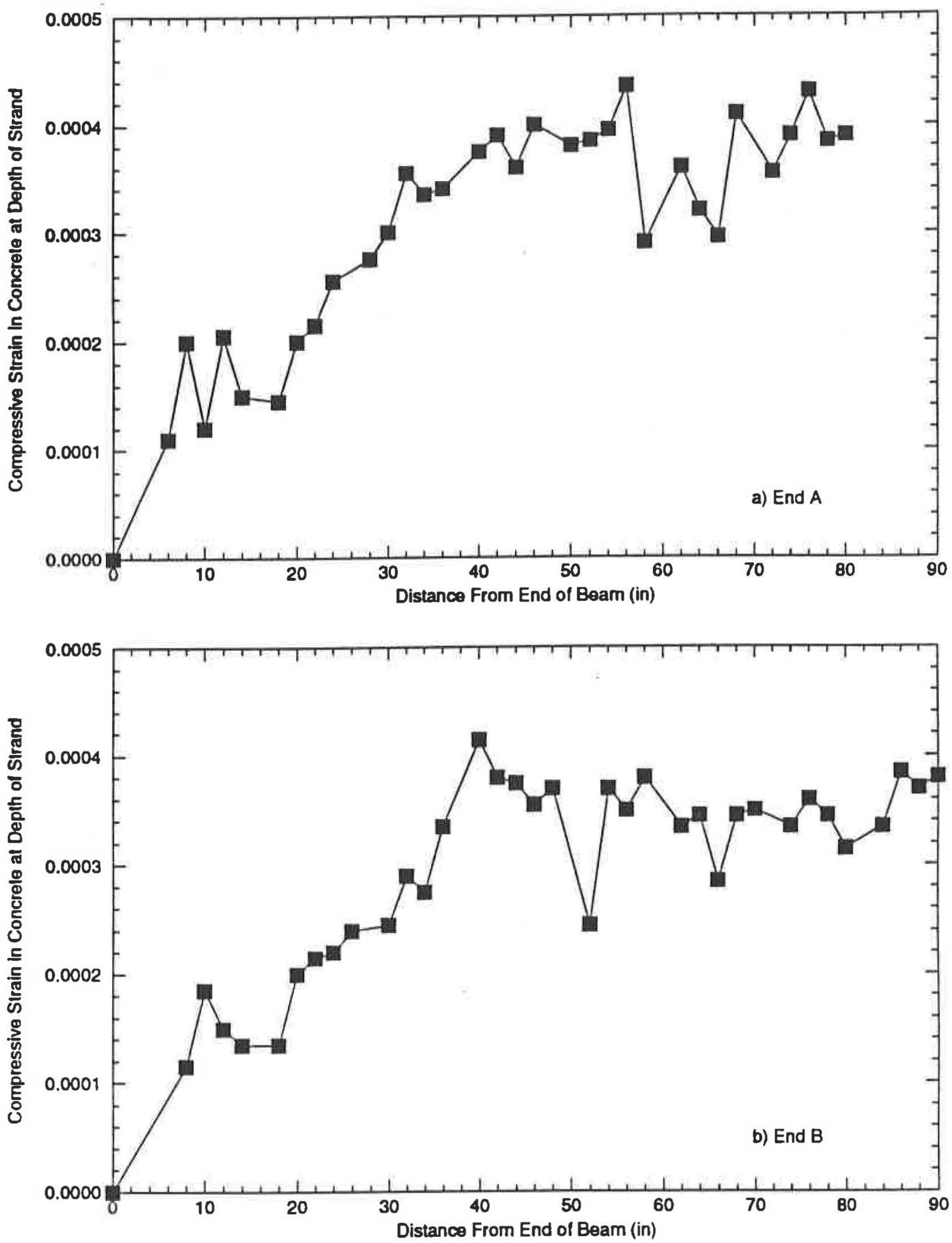


Figure A-6. All Raw Surface Strain Measurements Taken for Each End of Beam 6. (1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined.)

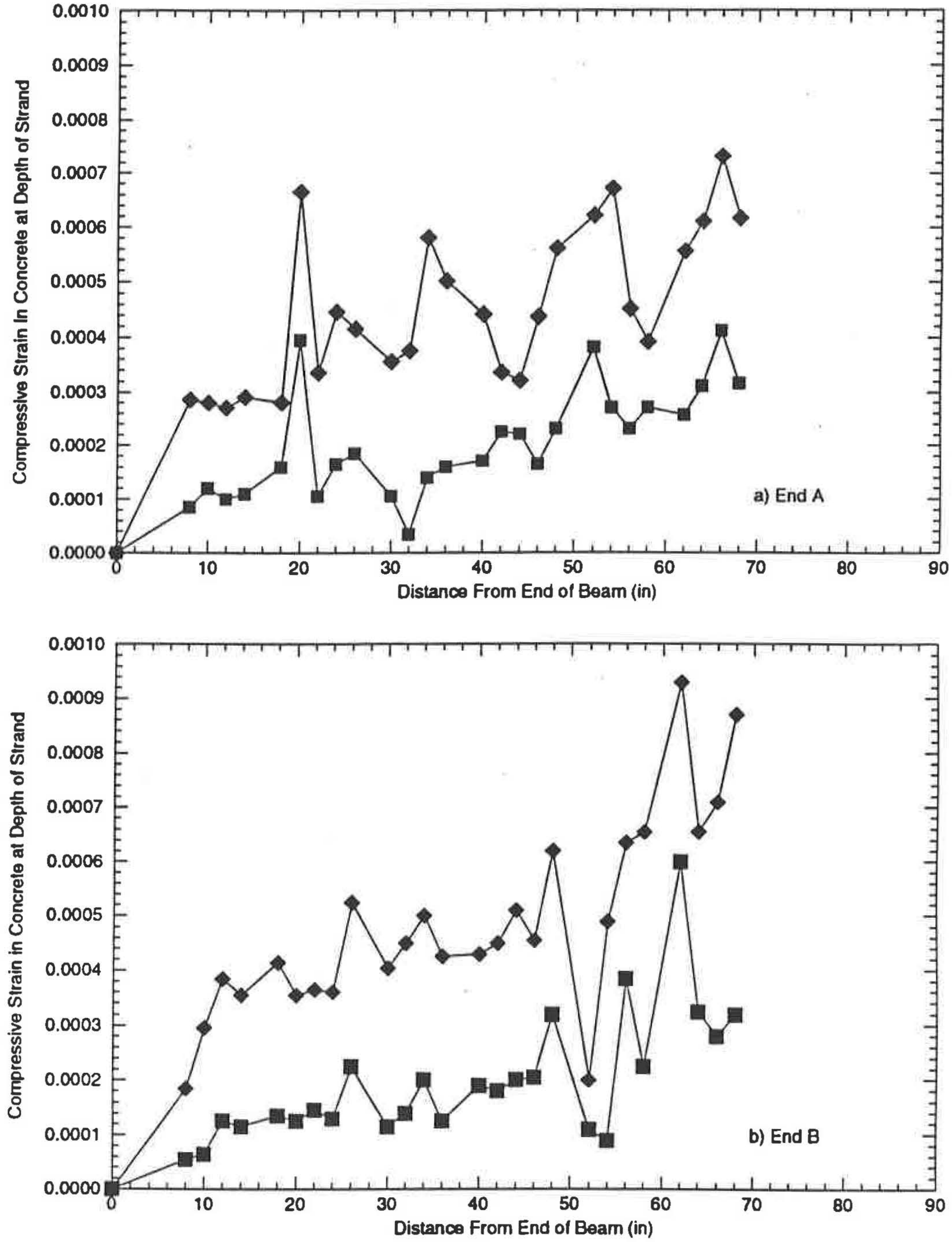
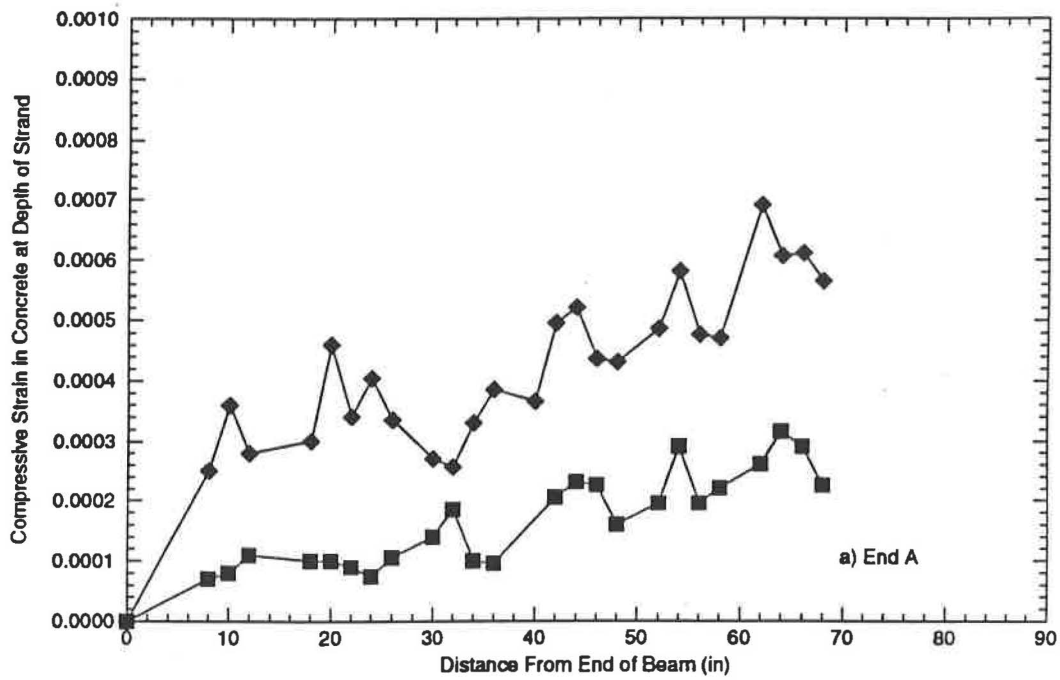


Figure A-7. All Raw Surface Strain Measurements Taken for Each End of Beam 7. (2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)



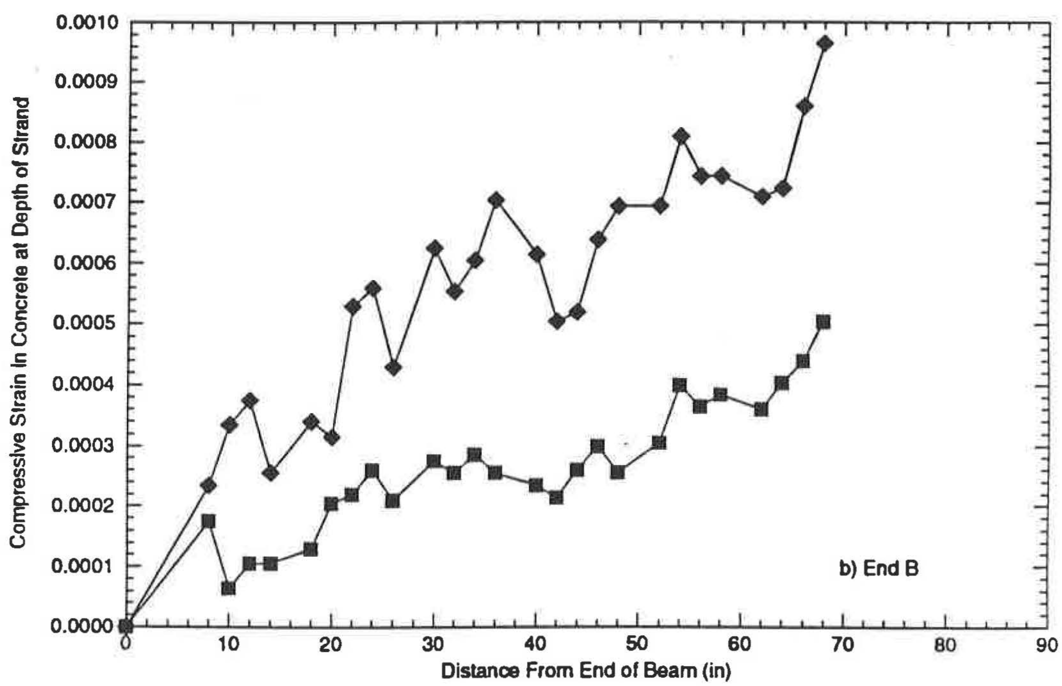
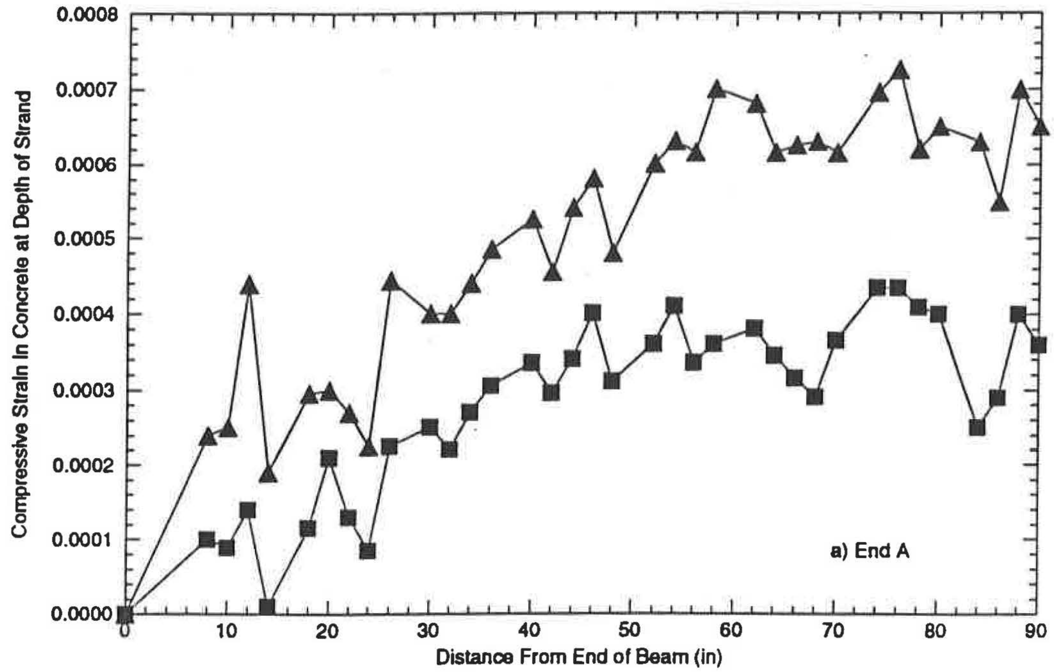


Figure A-8. All Raw Surface Strain Measurements Taken for Each End of Beam 8. (2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)



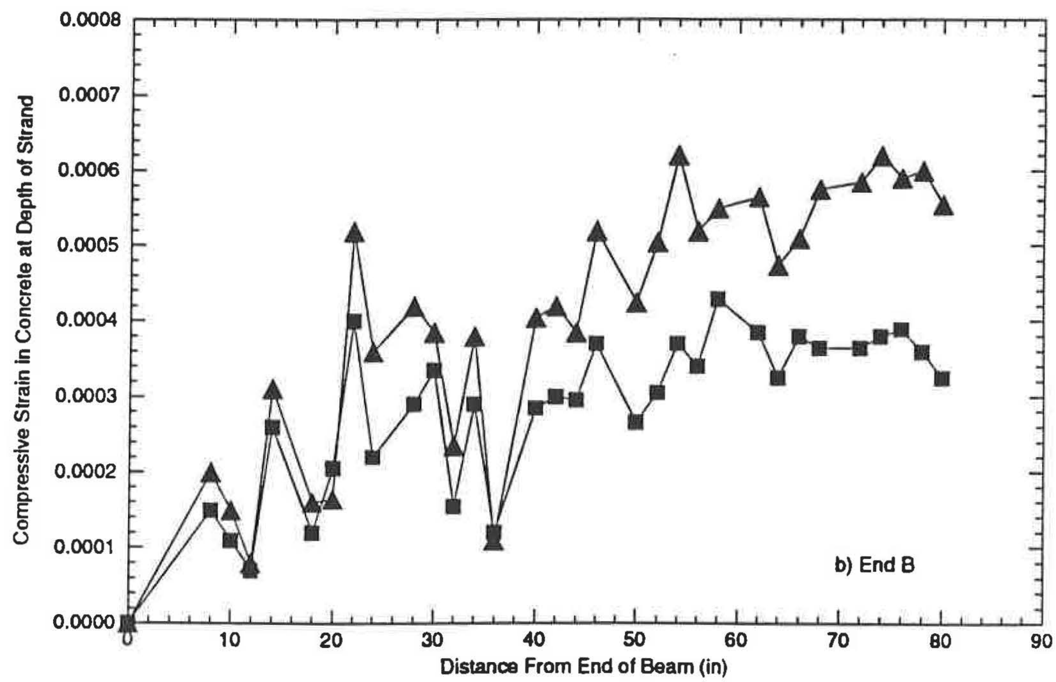


Figure A-9. All Raw Surface Strain Measurements Taken for Each End of Beam 9. (2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined.)

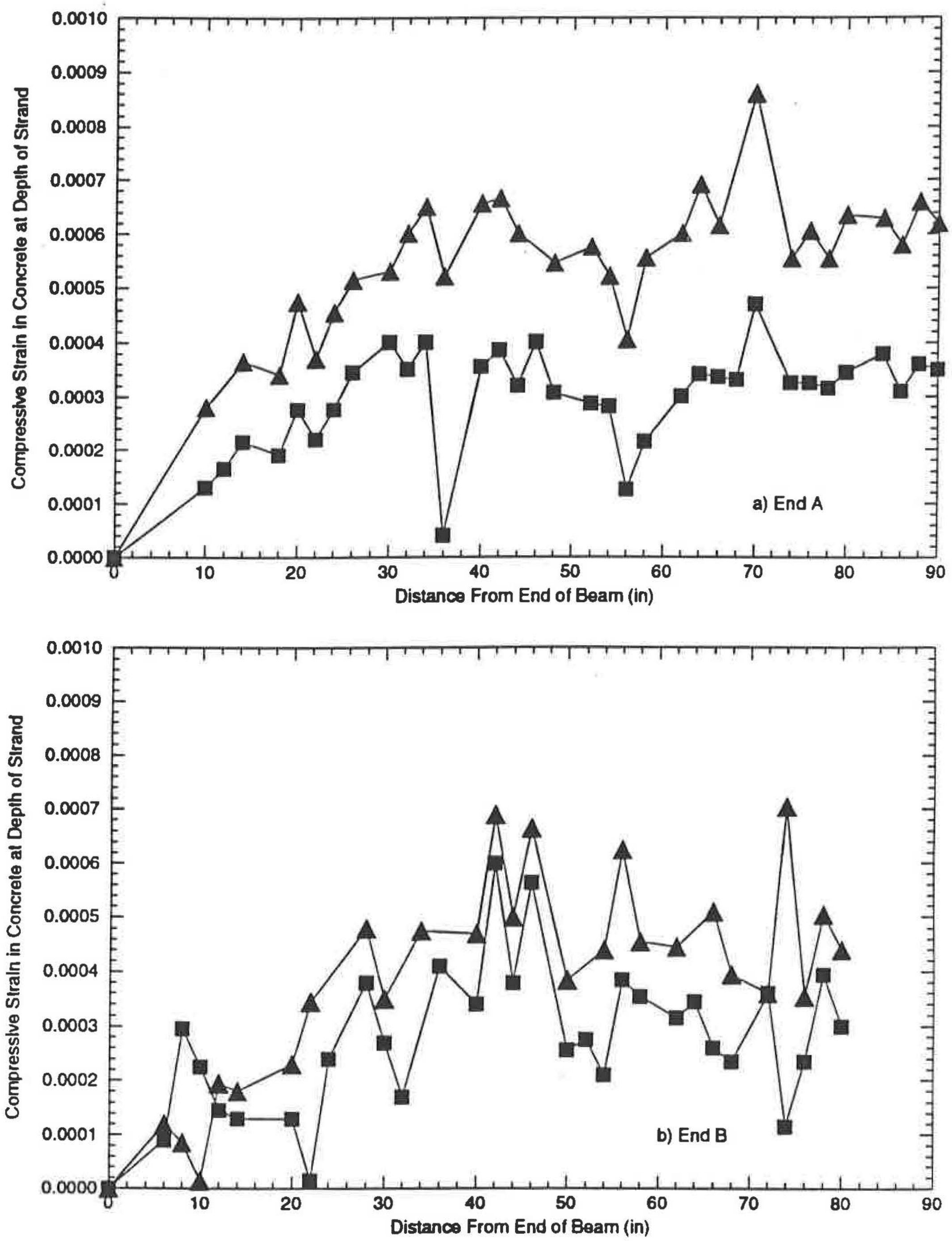


Figure A-10. All Raw Surface Strain Measurements Taken for Each End of Beam 10. (2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined.)

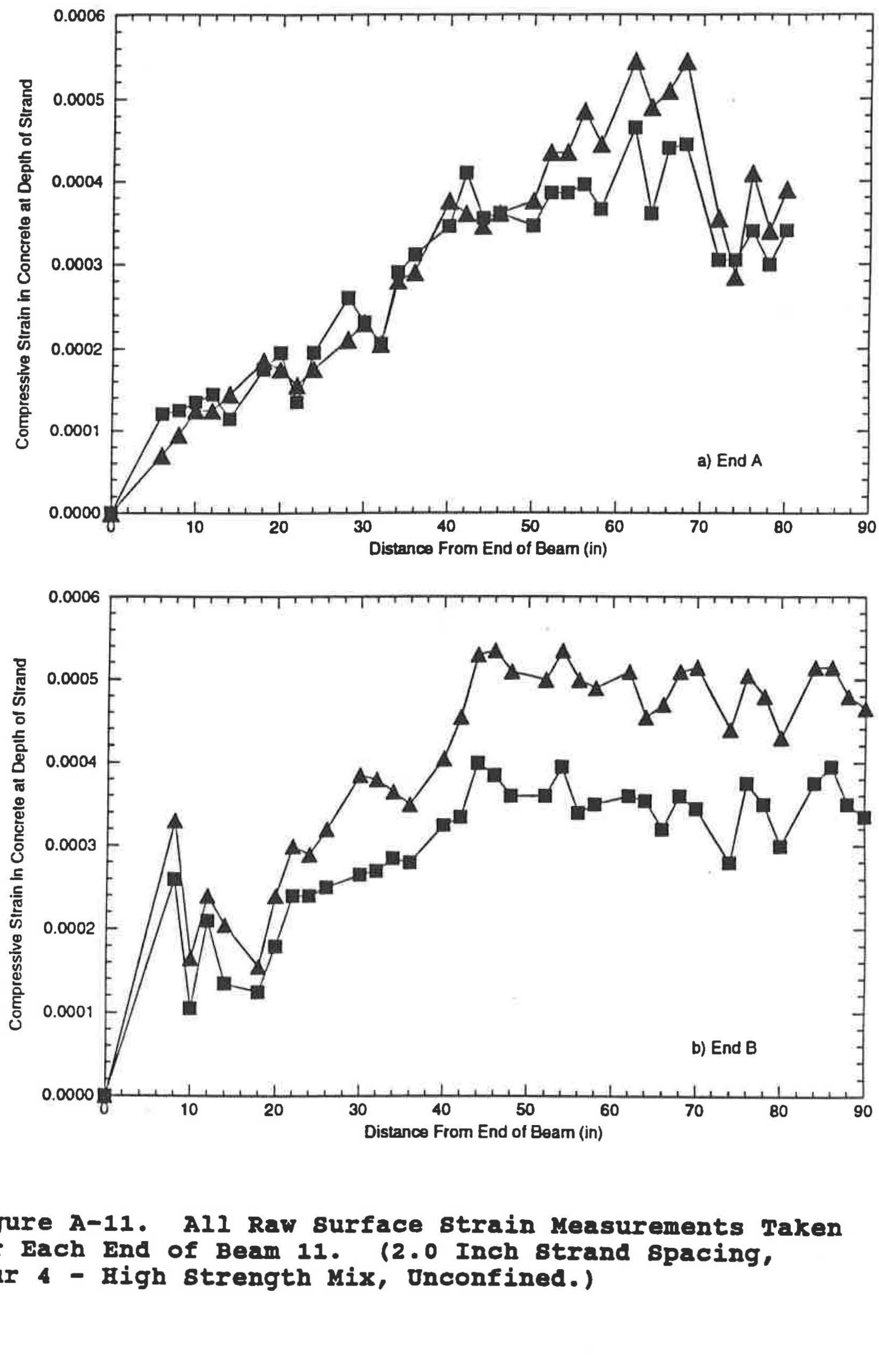


Figure A-11. All Raw Surface Strain Measurements Taken for Each End of Beam 11. (2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined.)

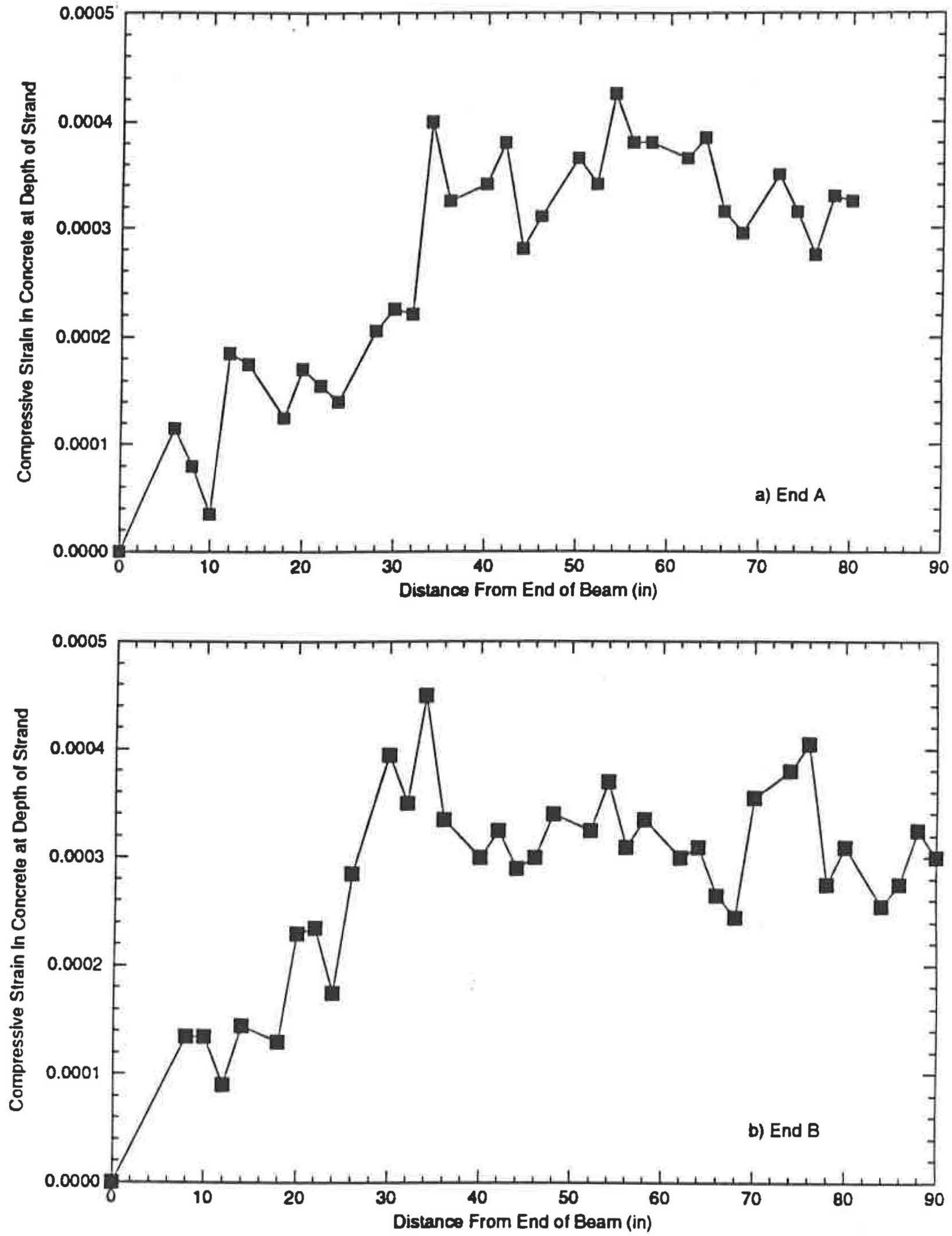


Figure A-12. All Raw Surface Strain Measurements Taken for Each End of Beam 12. (2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined.)

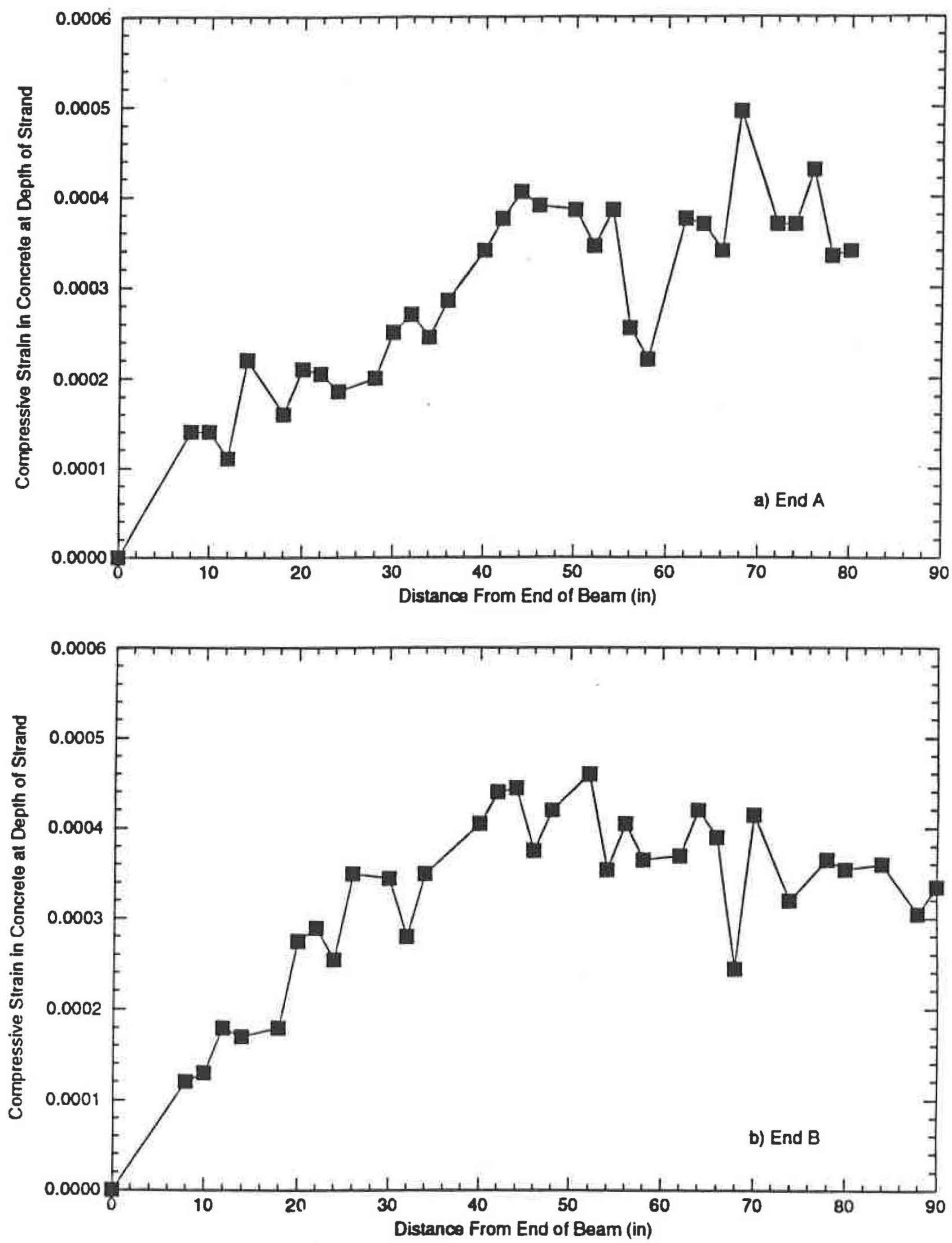


Figure A-13. All Raw Surface Strain Measurements Taken for Each End of Beam 13. (1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

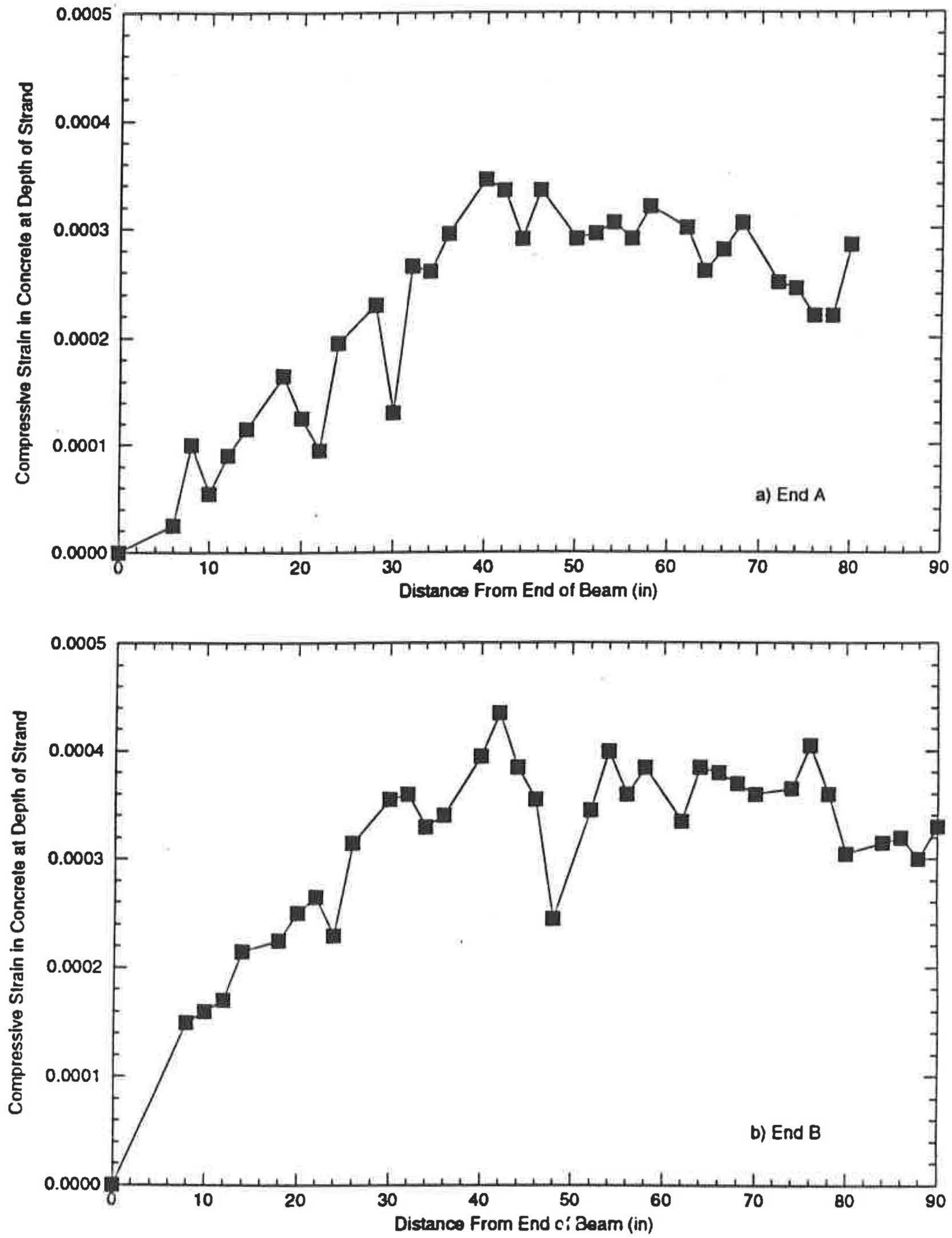


Figure A-14. All Raw Surface Strain Measurements Taken for Each End of Beam 14. (2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

APPENDIX B

B. REDUCED SURFACE STRAIN PLOTS

The surface strain plots in Appendix B include only reduced measurements immediately after transfer for each end of each beam. The graphs show the actual measurements taken at the time of transfer. It was a concern that the strain due to the self-weight moment of the beam (due to the simple support condition caused by camber) could affect the strain measurements. The self-weight strain at the effective depth of strand was investigated and found to be at least an order of magnitude smaller than the prestressing strain. The plots in Appendix B are a result of dropping "bad points" through the simple statistical analysis described in Chapter 3.

Each figure number coincides with the beam number on which the surface strain measurements were taken. Each figure includes the surface strain measurements for each end of a given beam. The top plot in each figure is the surface strain versus distance from the end of the beam for end A. The bottom plot in each figure is the surface strain versus distance from the end of the beam for end B. The figure titles include the important information about each beam: strand spacing, pour number and concrete strength category, and confinement information.

The horizontal dashed line in each plot shows the average strain plateau for the reduced data. The magnitude of the average strain is given just above the horizontal dashed line. The vertical dashed line in each plot shows the final estimated transfer length. The magnitude of the transfer length is given just to the left of the vertical dashed line.

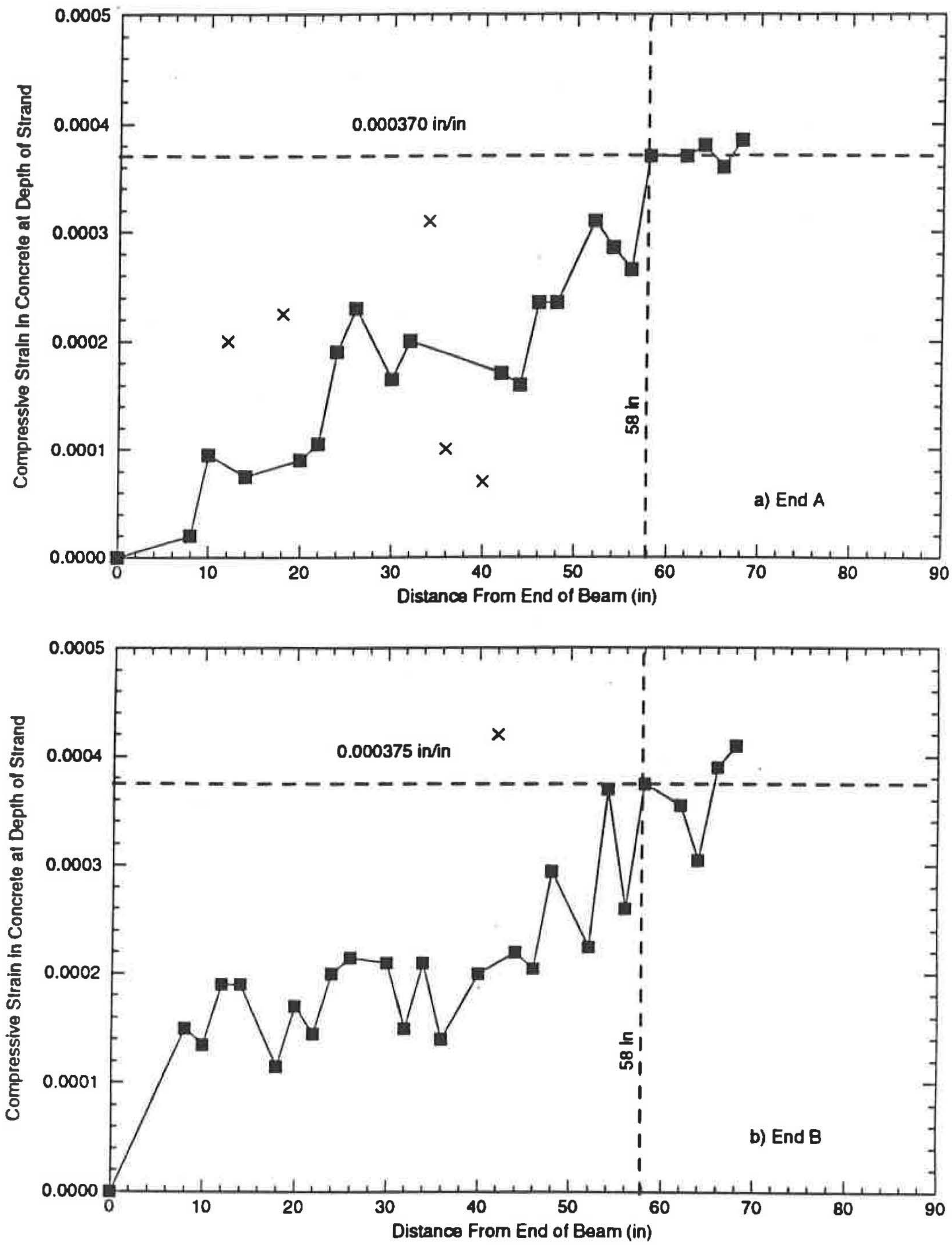


Figure B-1. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 1. (1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

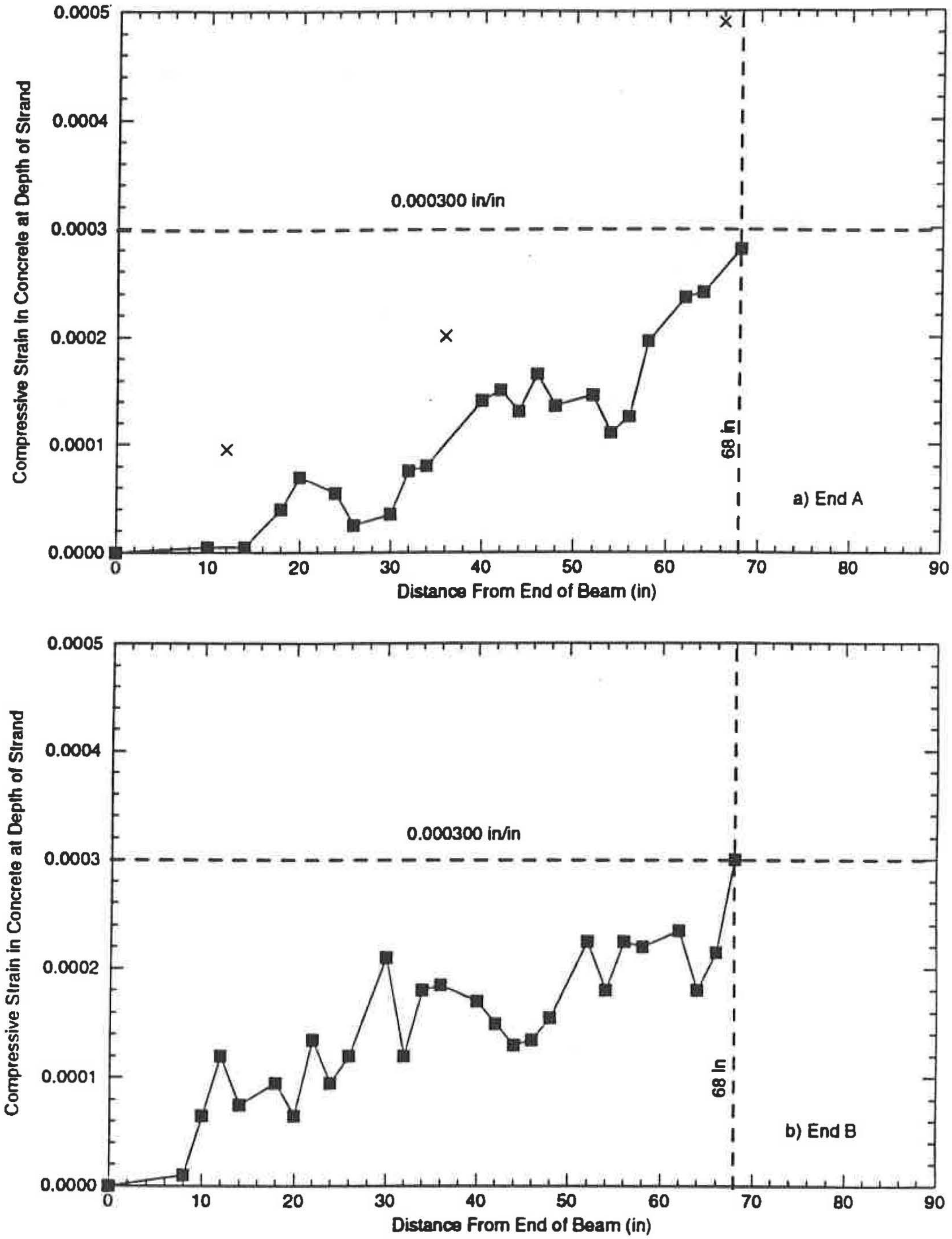


Figure B-2. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 2. (1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

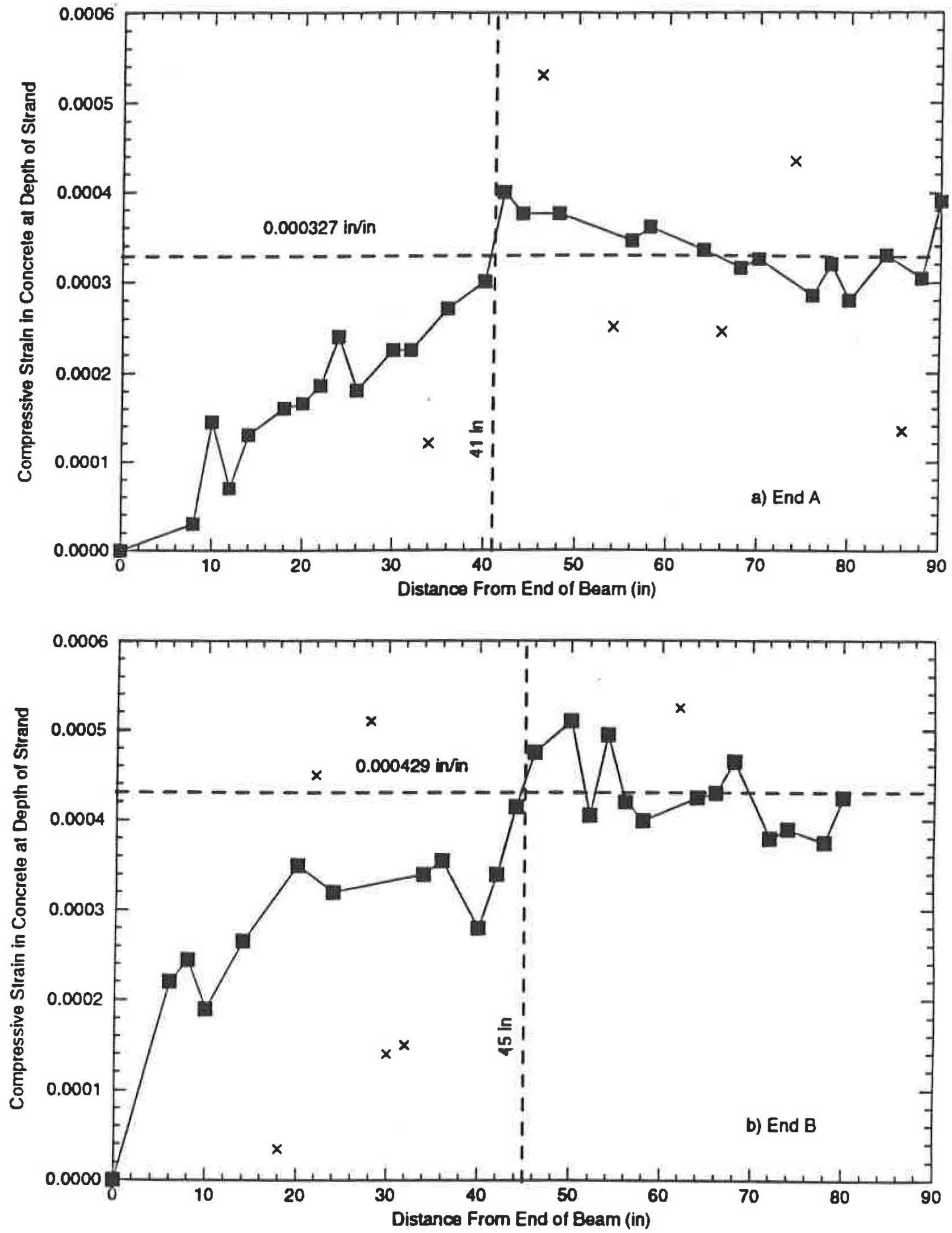


Figure B-3. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 3. (1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined.)

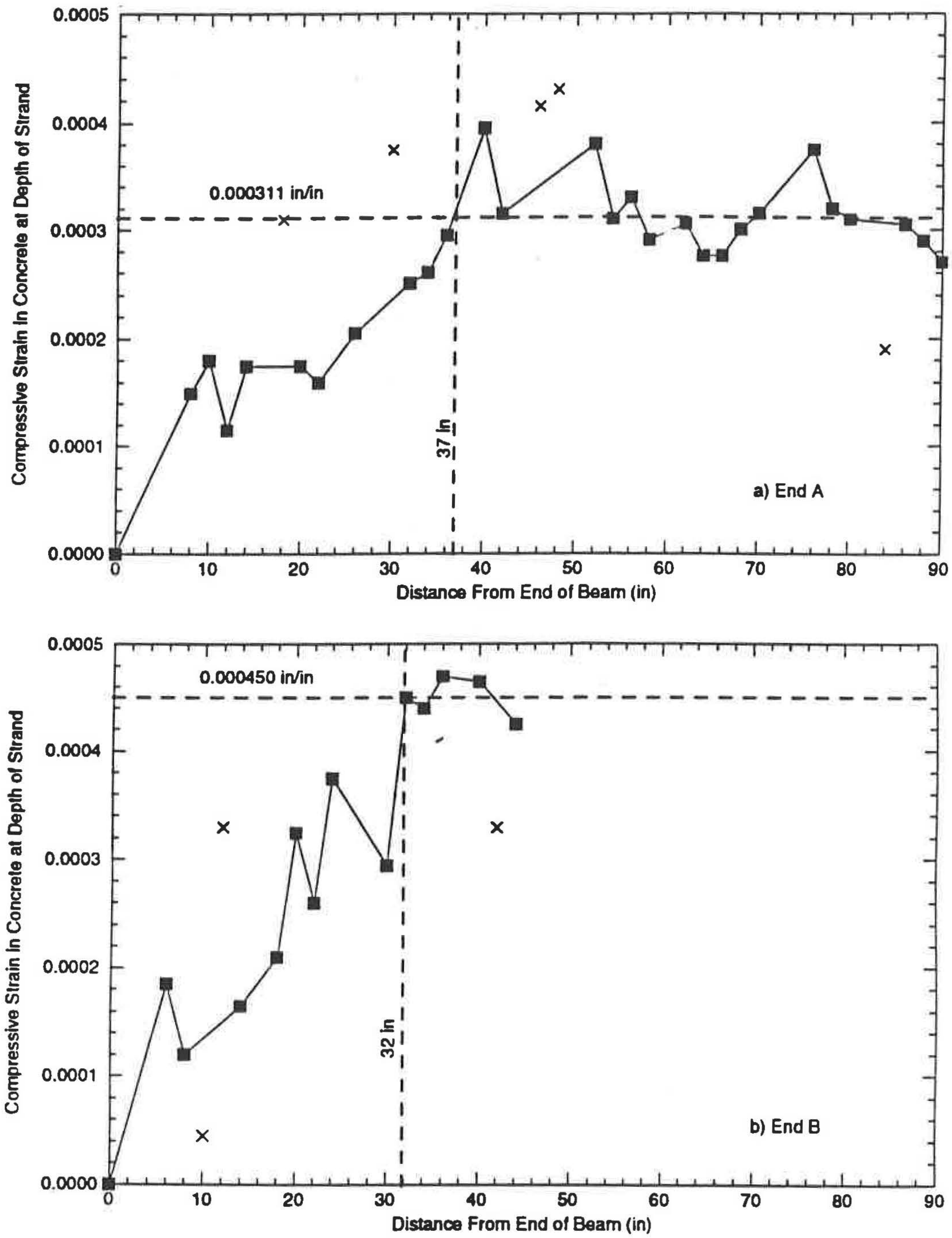


Figure B-4. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 4. (1.75 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined.)

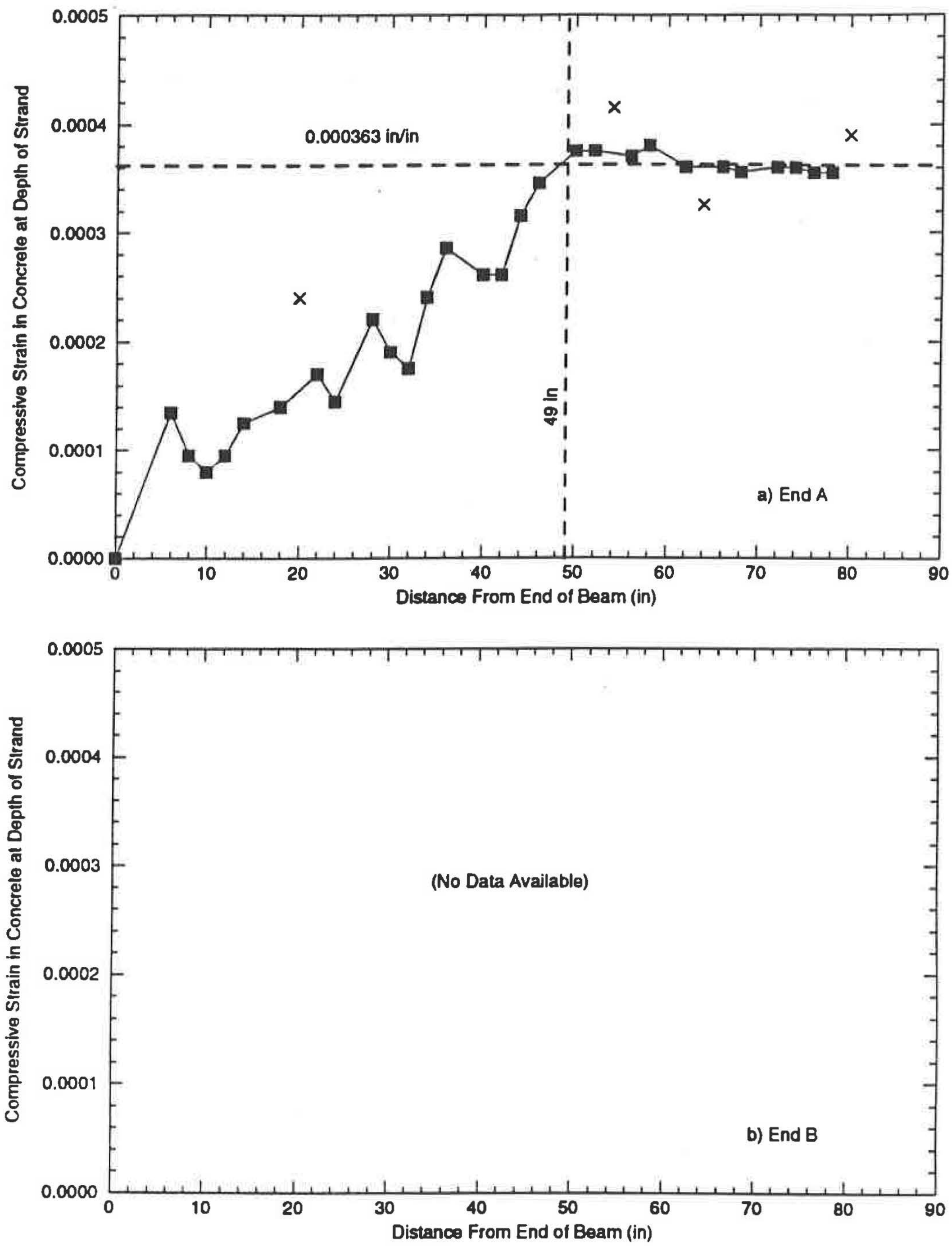


Figure B-5. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 5. (1.75 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined.)

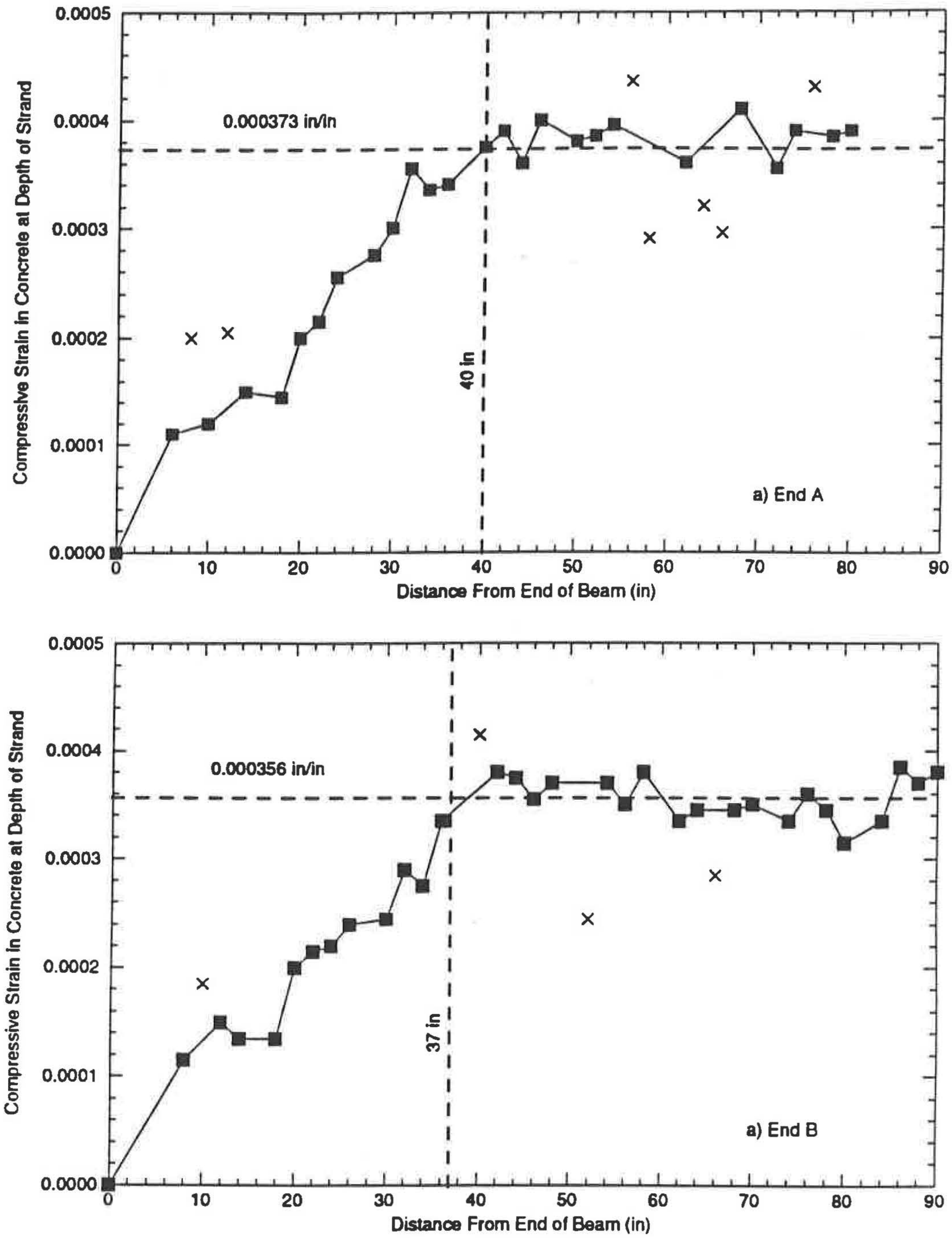
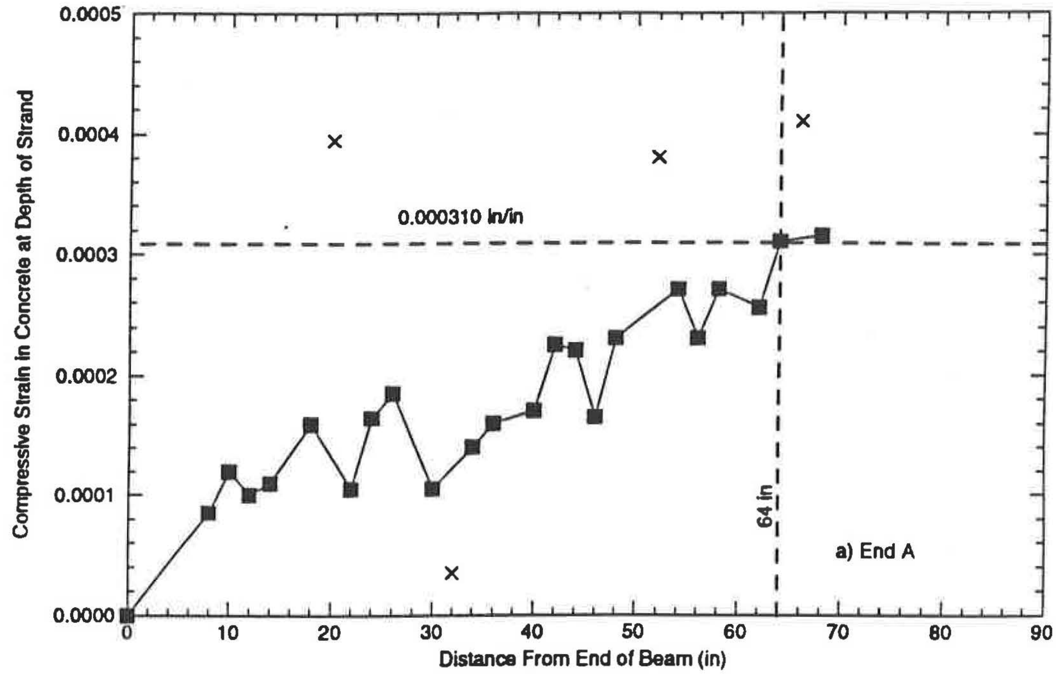


Figure B-6. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 6. (1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined.)



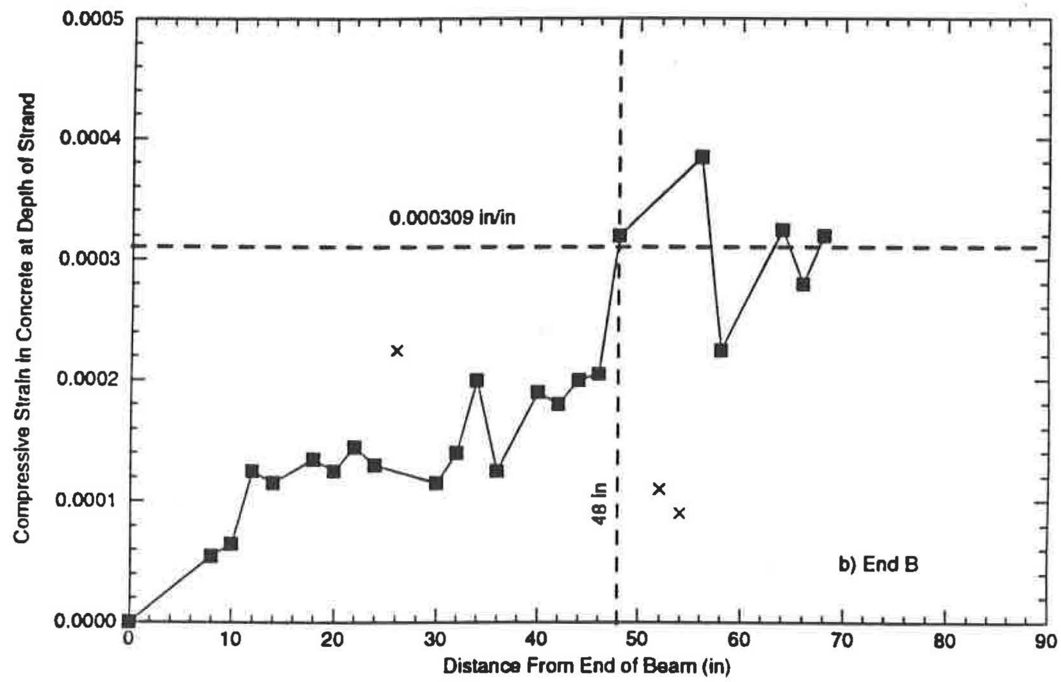


Figure B-7. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 7. (2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

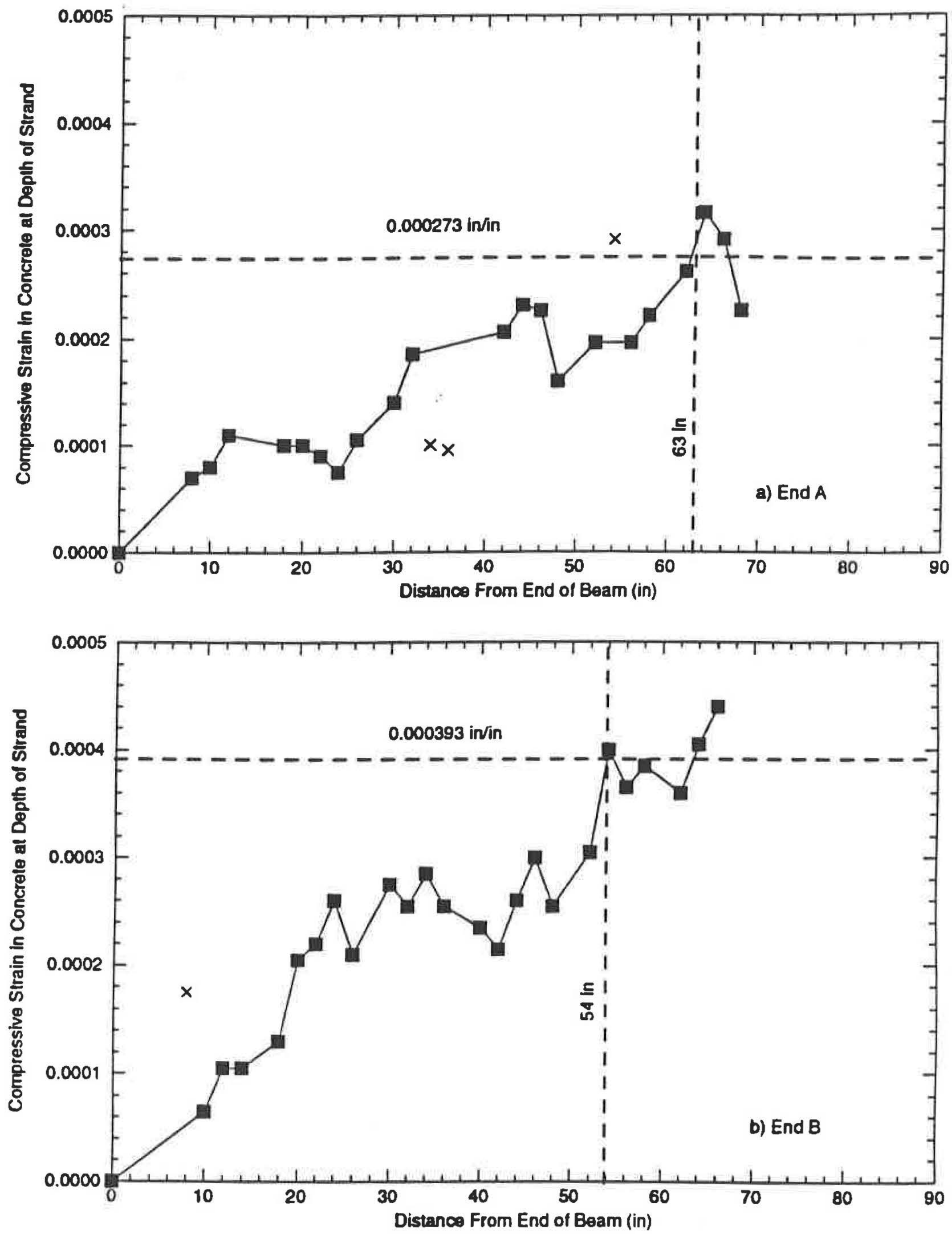


Figure B-8. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 8. (2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined.)

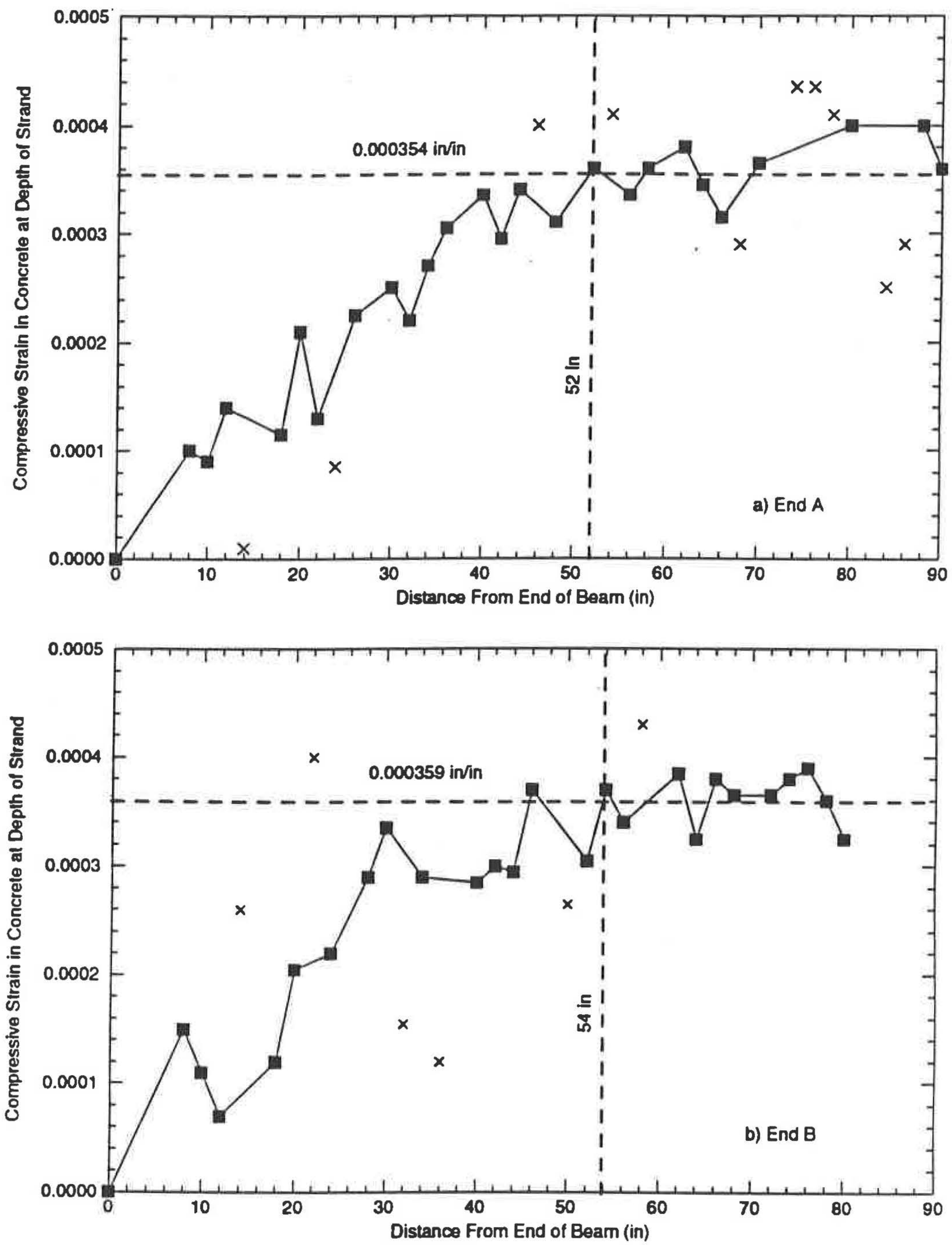
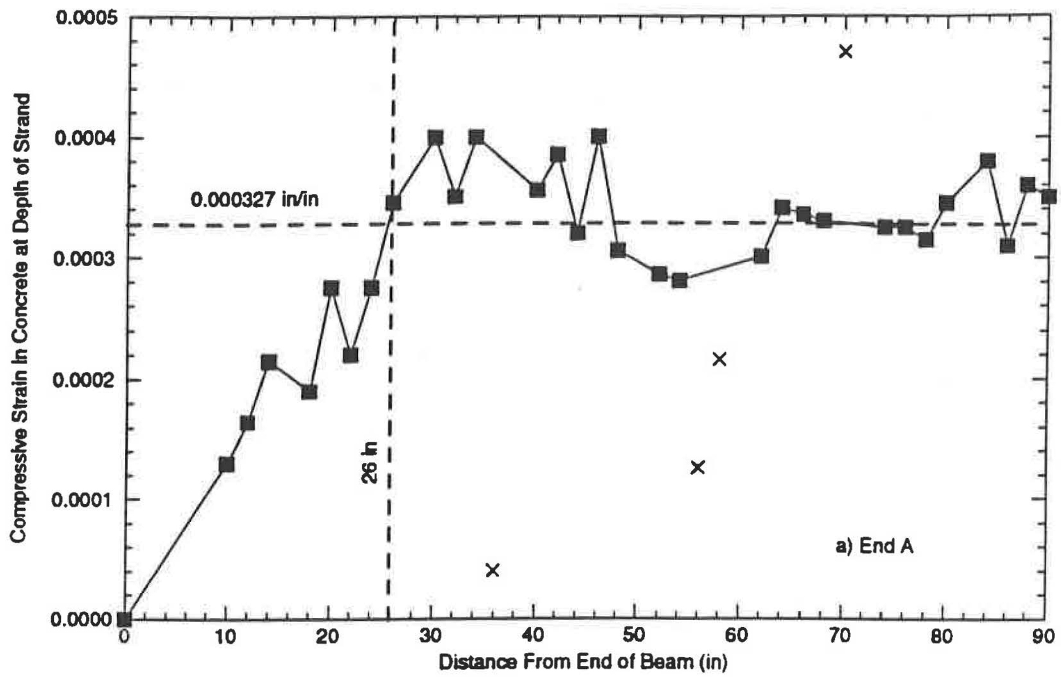


Figure B-9. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 9. (2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined.)



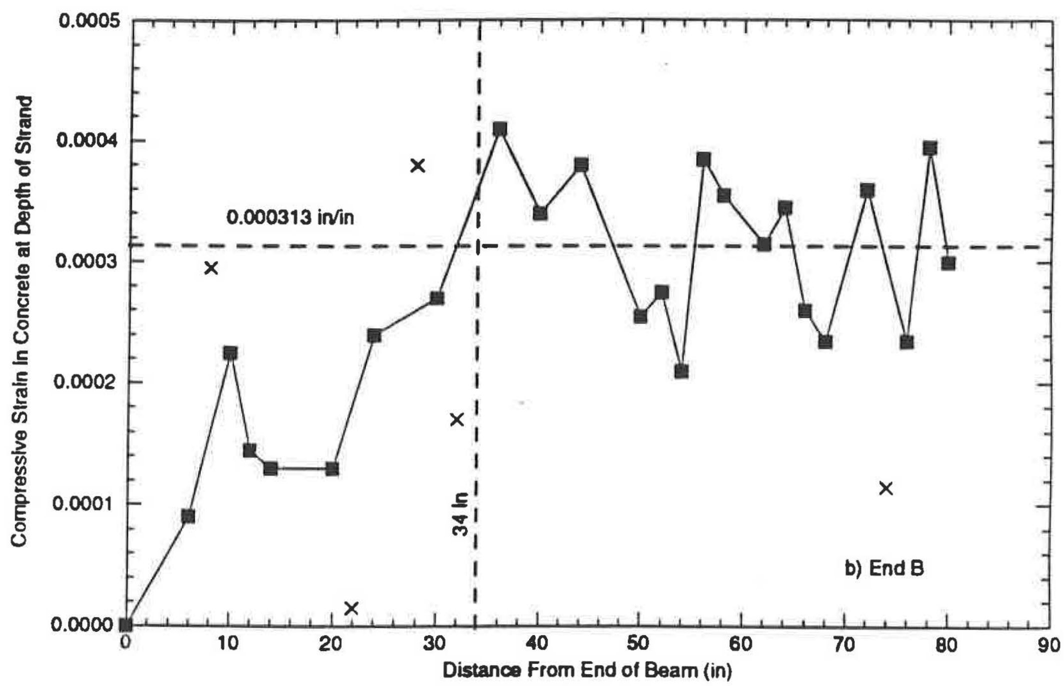
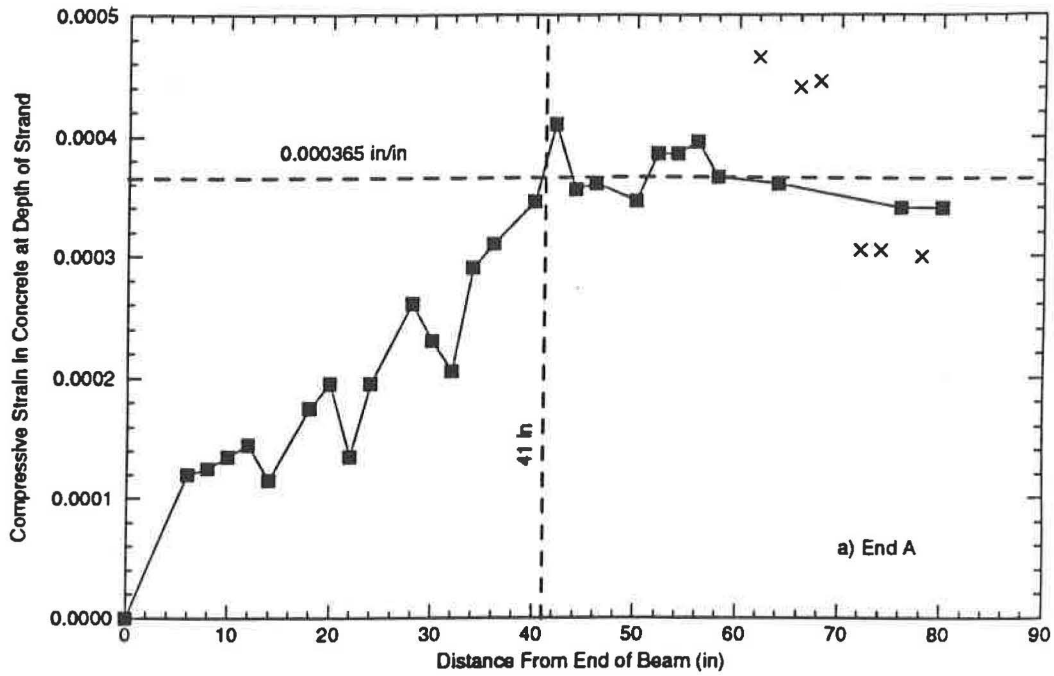


Figure B-10. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 10. (2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined.)



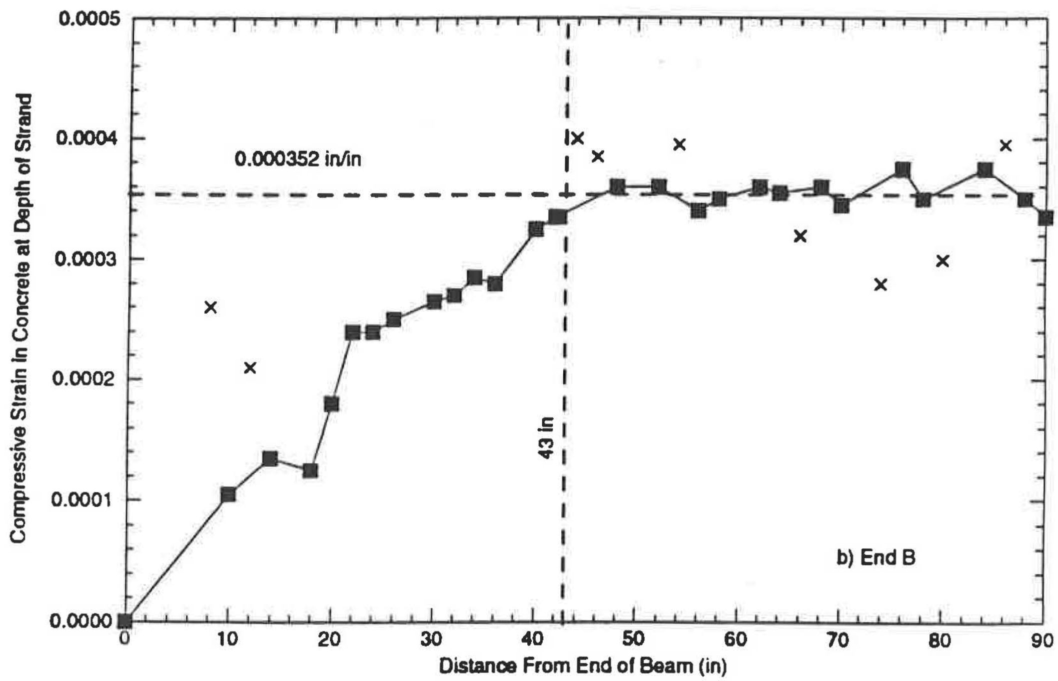


Figure B-11. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 11. (2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined.)

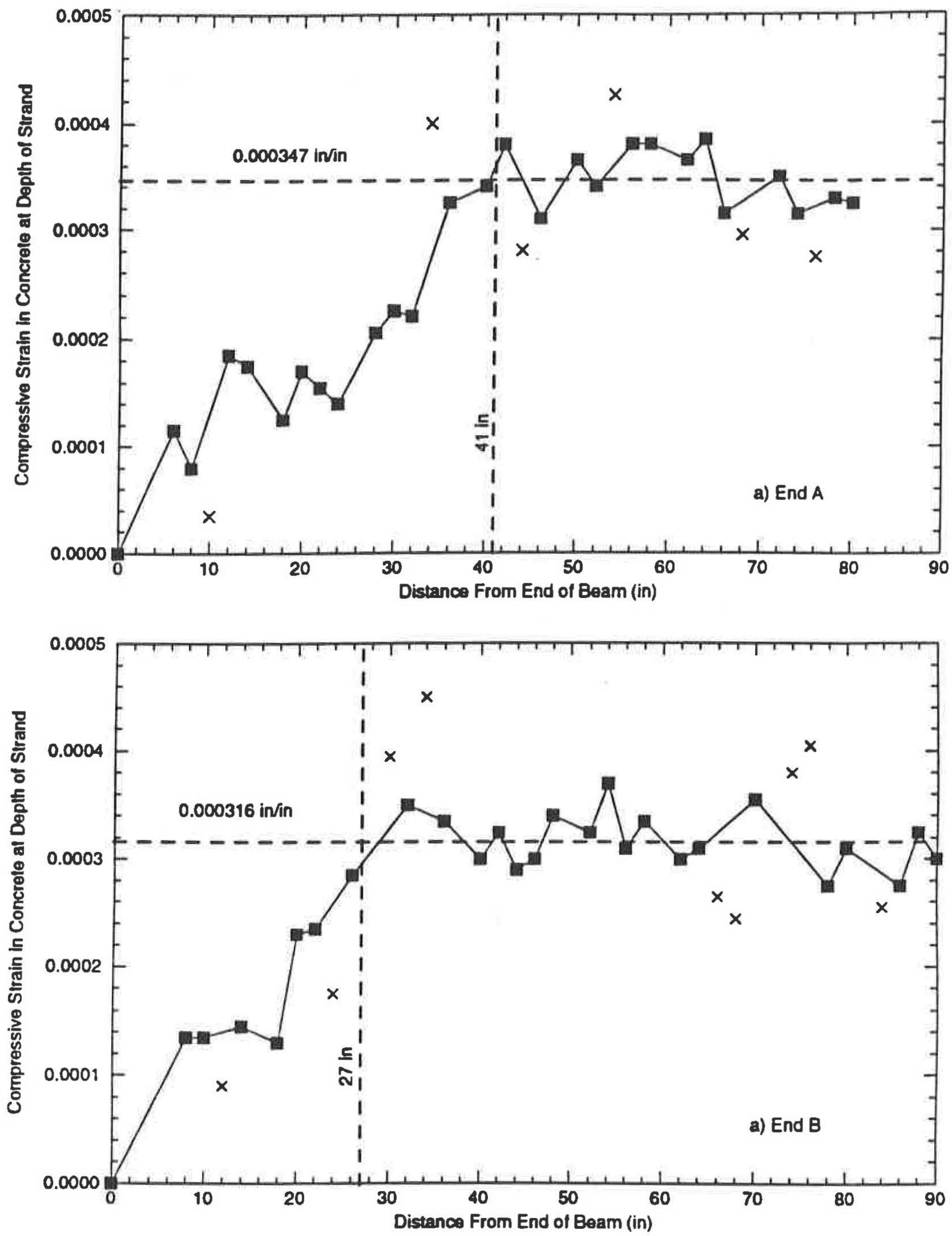


Figure B-12. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 12. (2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined.)

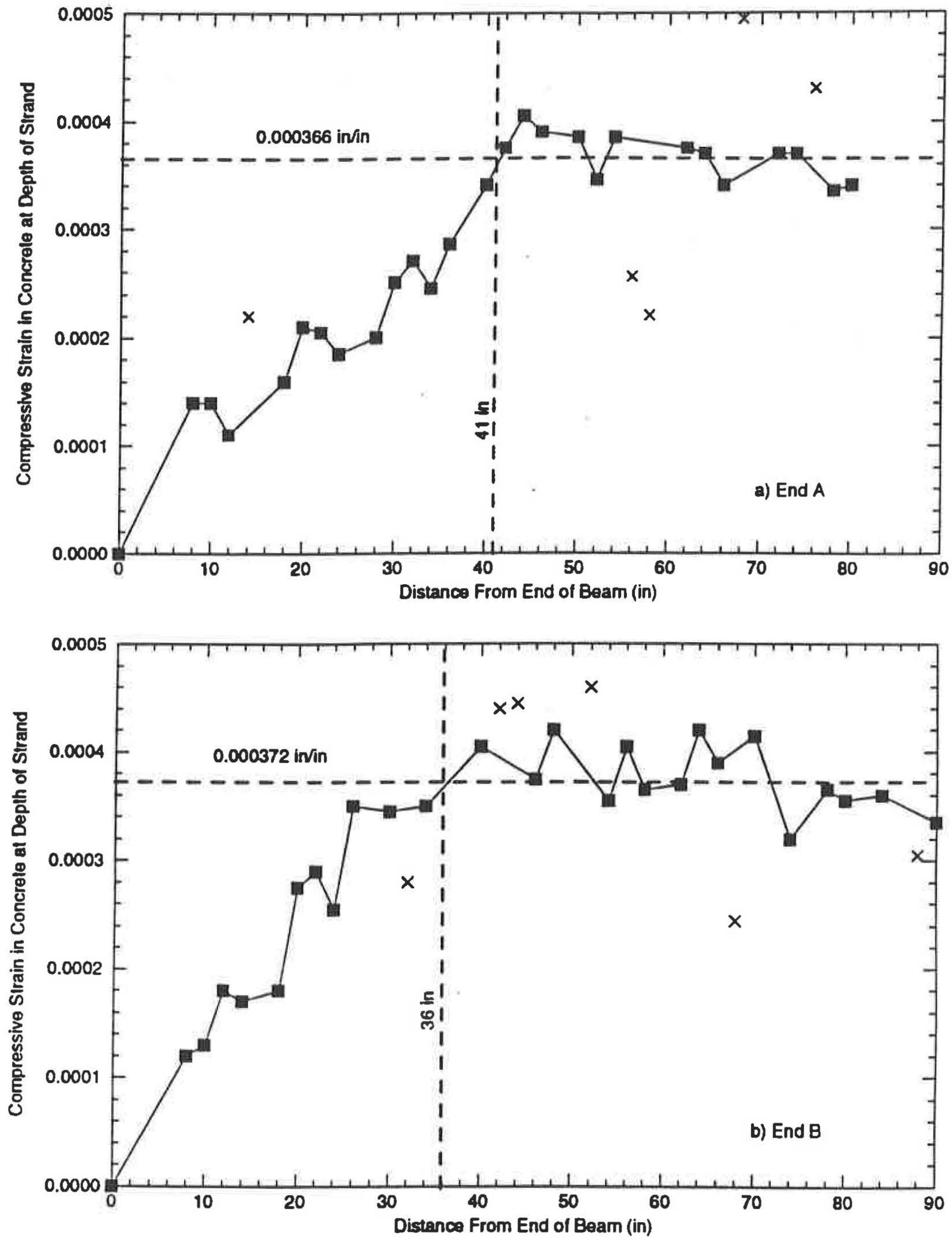


Figure B-13. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 13. (1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

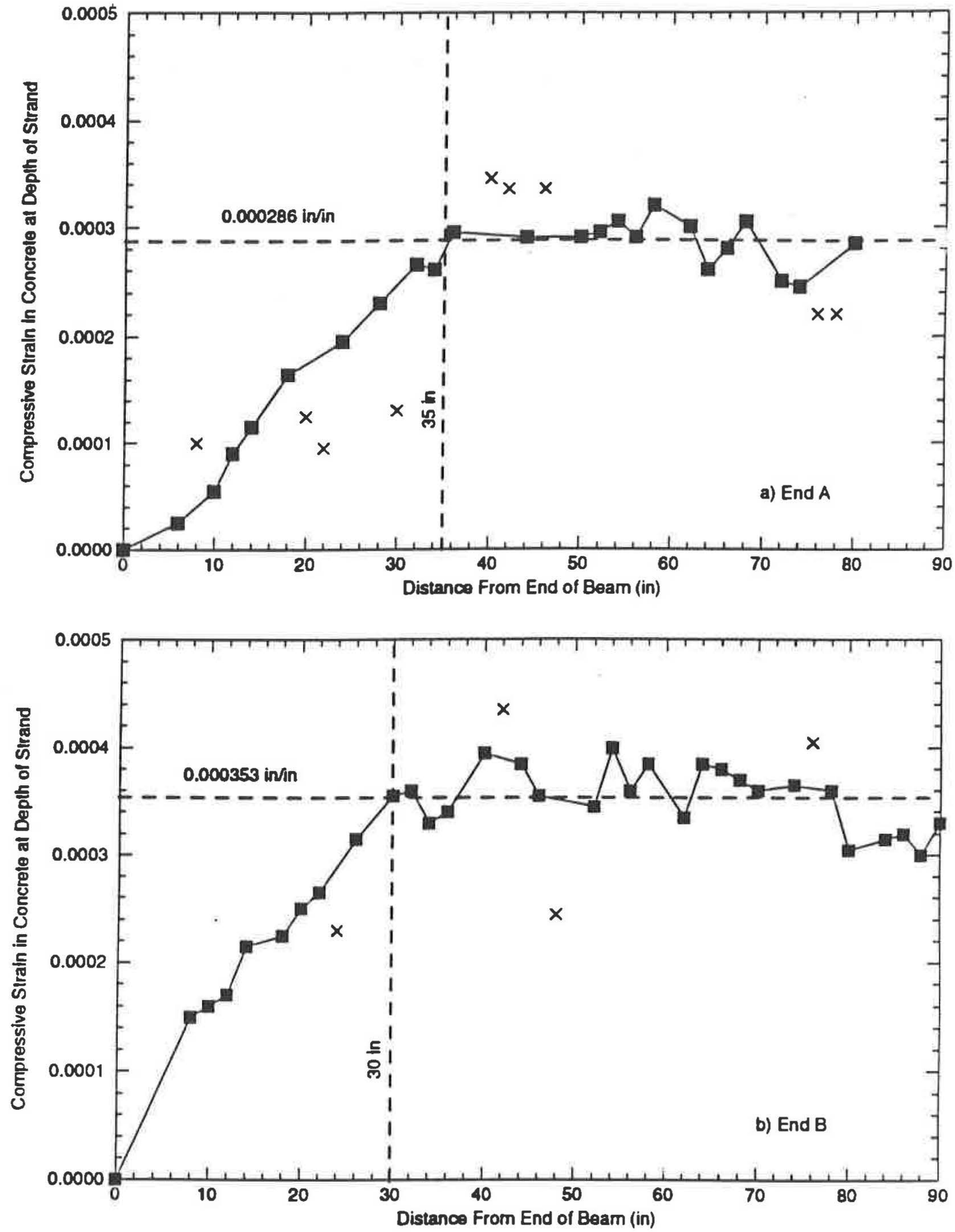


Figure B-14. Reduced Surface Strain Measurements Immediately After Transfer for Each End of Beam 14. (2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined.)

APPENDIX C

C. FLEXURAL TEST DATA

The plots in Appendix C include all pertinent data taken during each flexural test as described in Chapter 3. Each figure includes four plots:

a) moment at the point of load versus strand slip for the top row of strands at the tested end,

b) moment at the point of load versus strand slip for the middle row of strands at the tested end,

c) moment at the point of load versus strand slip for the bottom row of strands at the tested end, and

d) moment at the point of load versus deflection at the point of load.

The top three plots (a,b,c) of each figure show the slips measured for each of the three strands (left, middle, right) in a given row (top, middle, bottom).

Each figure number coincides with the test number of the flexural test performed. The figure titles include the important information about each test: beam number and end being tested, strand spacing, pour number and concrete strength category of the beam, confinement information, embedment length, and failure mode.

The following legend shows the line types corresponding to the left, middle, and right strands in each row of strands. This legend applies to the strand slip plots in each figure. Each figure shows the slip of nine strands:

a) left, middle, and right strands of the top row,
b) left, middle, and right strands of the middle row, and
c) left, middle, and right strands of the bottom row.

Left Strand of the Given Row

Middle Strand of the Given Row

Right Strand of the Given Row

No data is available for test 19 due to problems with the data acquisition unit.

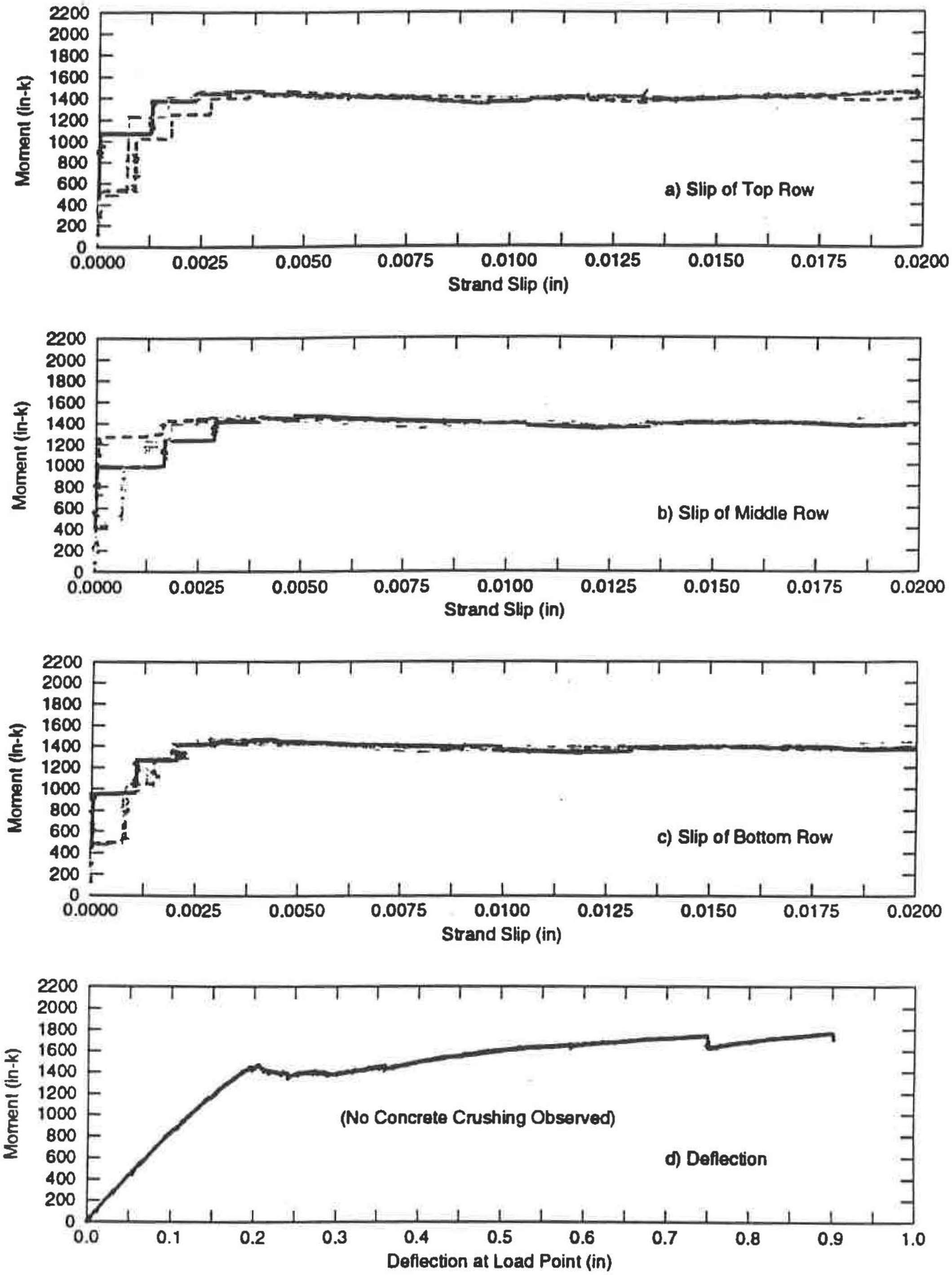


Figure C-1. Flexural Test Data for Test 1. (Beam 2, End A, 1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 96 Inch Embedment Length, Bond Failure.)

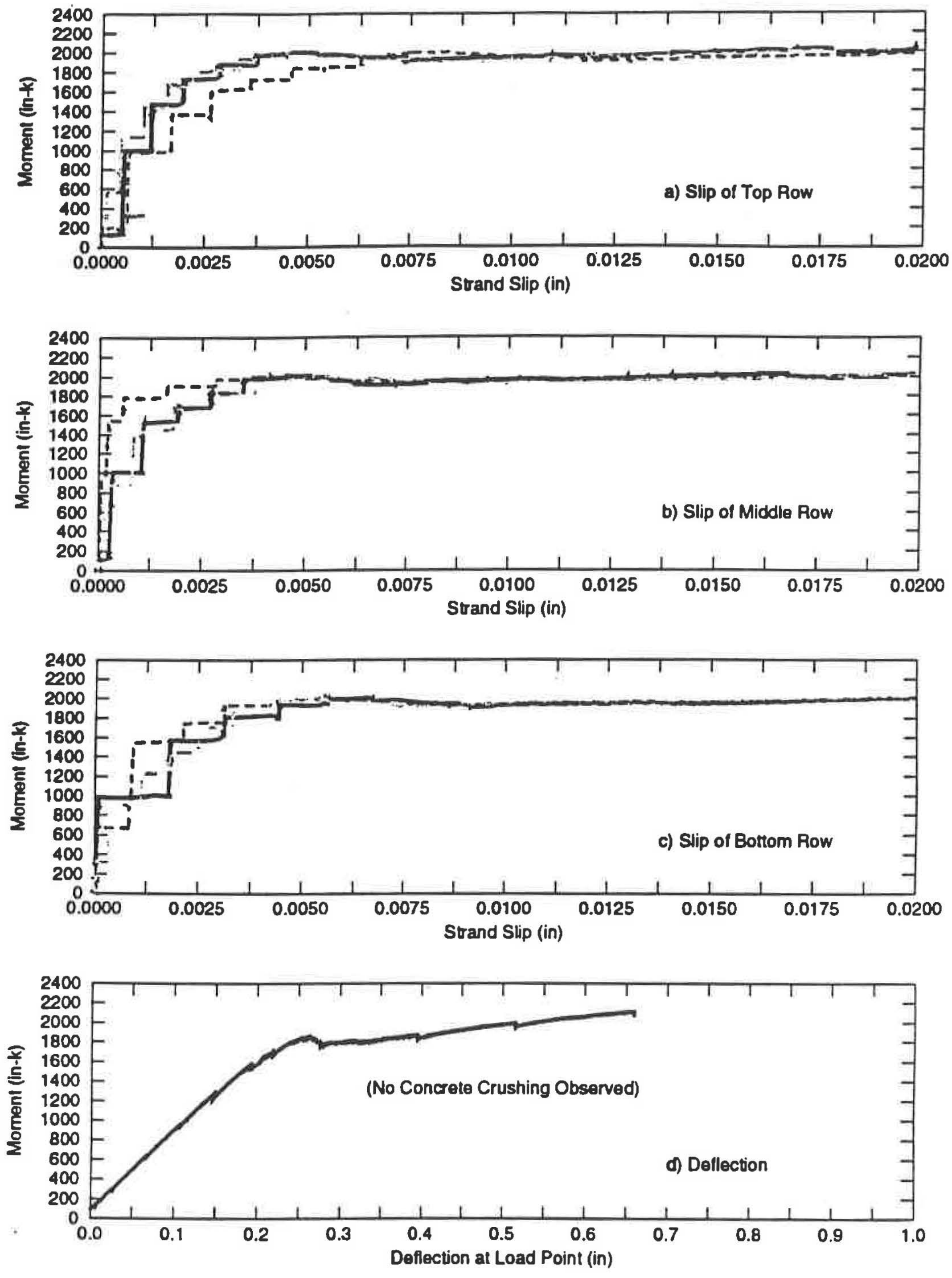


Figure C-2. Flexural Test Data for Test 2. (Beam 1, End A, 1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 114 Inch Embedment Length, Bond Failure.)

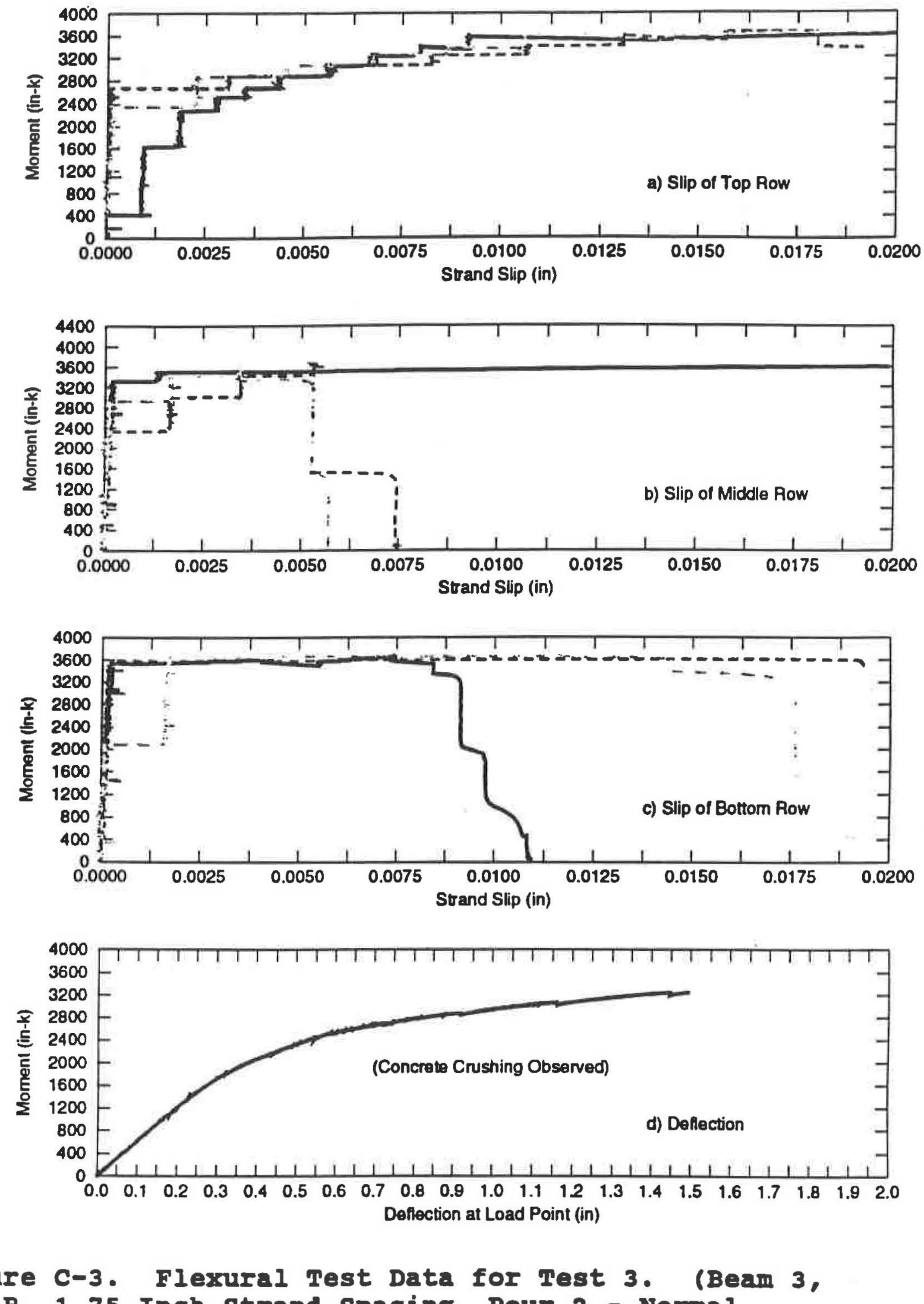


Figure C-3. Flexural Test Data for Test 3. (Beam 3, End B, 1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

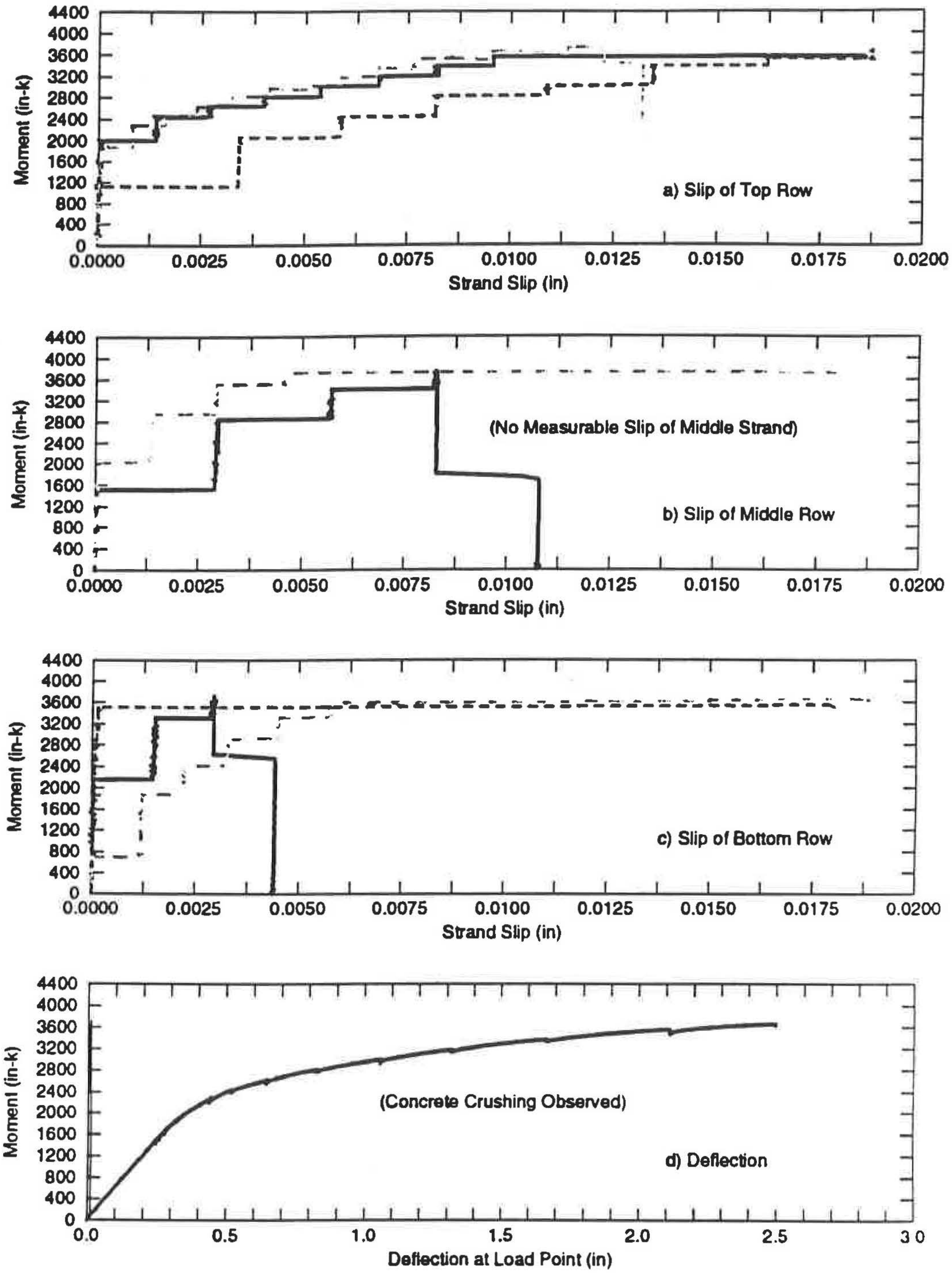


Figure C-4. Flexural Test Data for Test 4. (Beam 3, End A, 1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

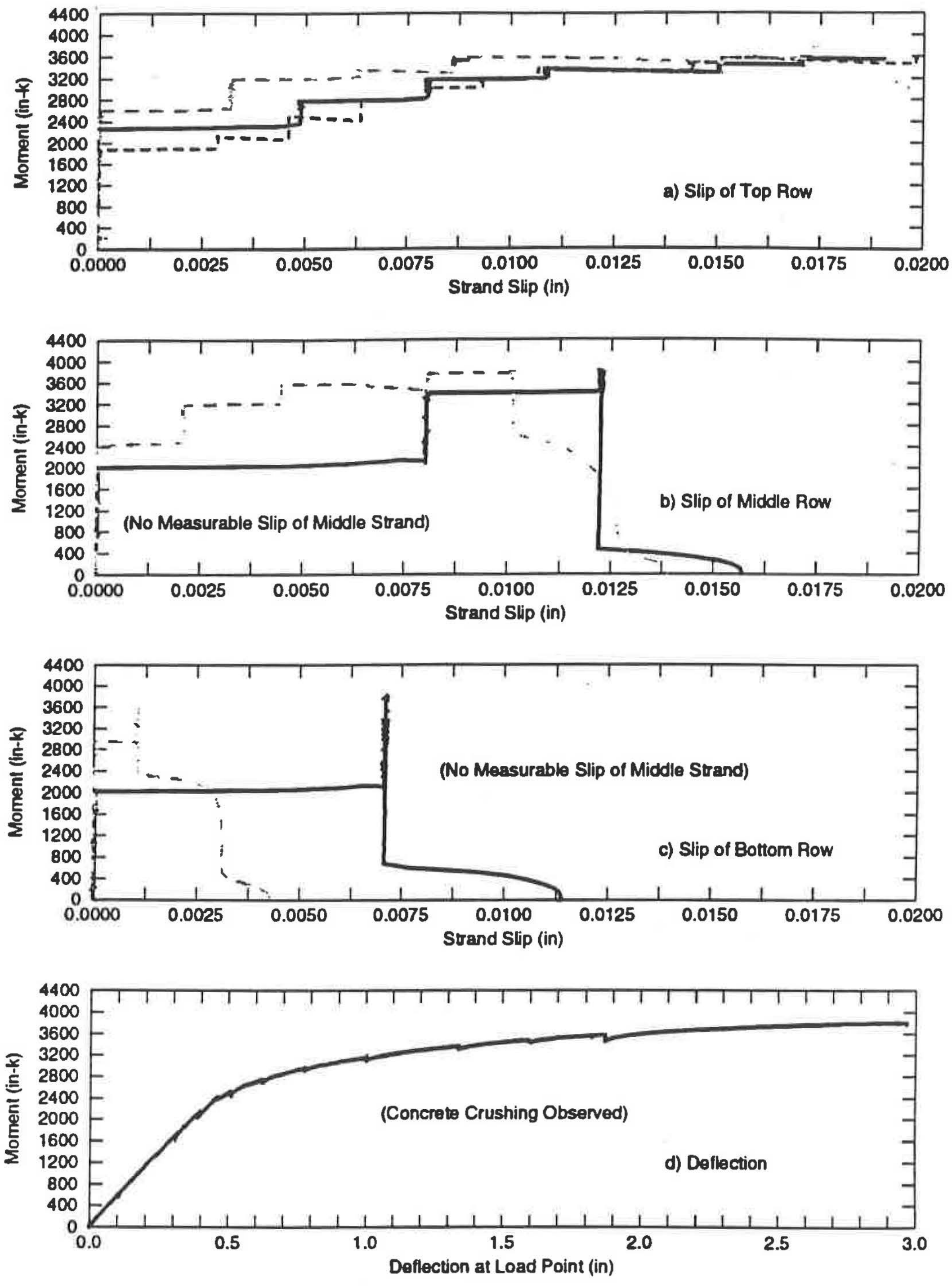


Figure C-5. Flexural Test Data for Test 5. (Beam 6, End A, 1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 168 Inch Embedment Length, Flex/Slip Failure.)

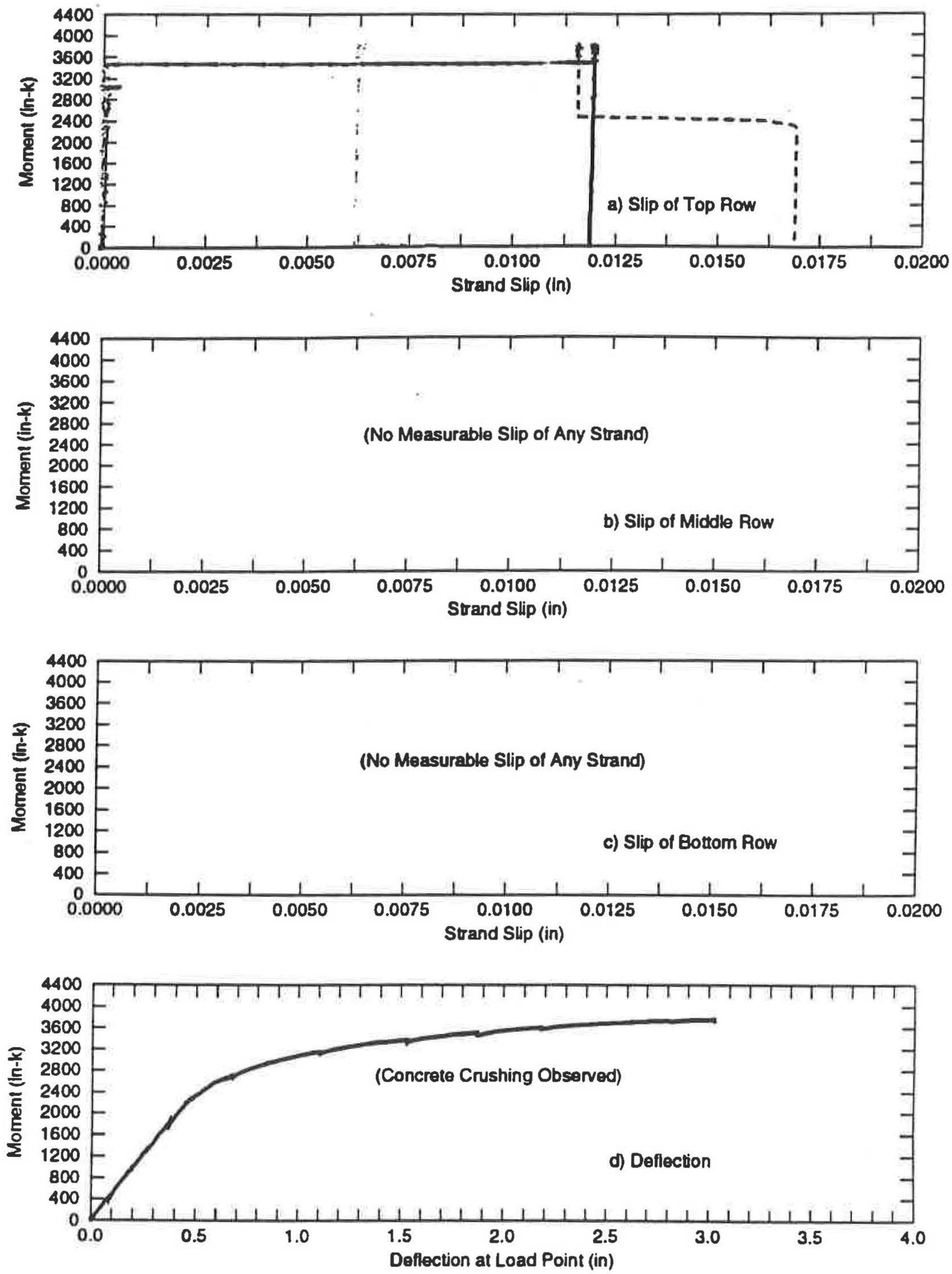


Figure C-6. Flexural Test Data for Test 6. (Beam 6, End B, 1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 180 Inch Embedment Length, Flex/Slip Failure.)

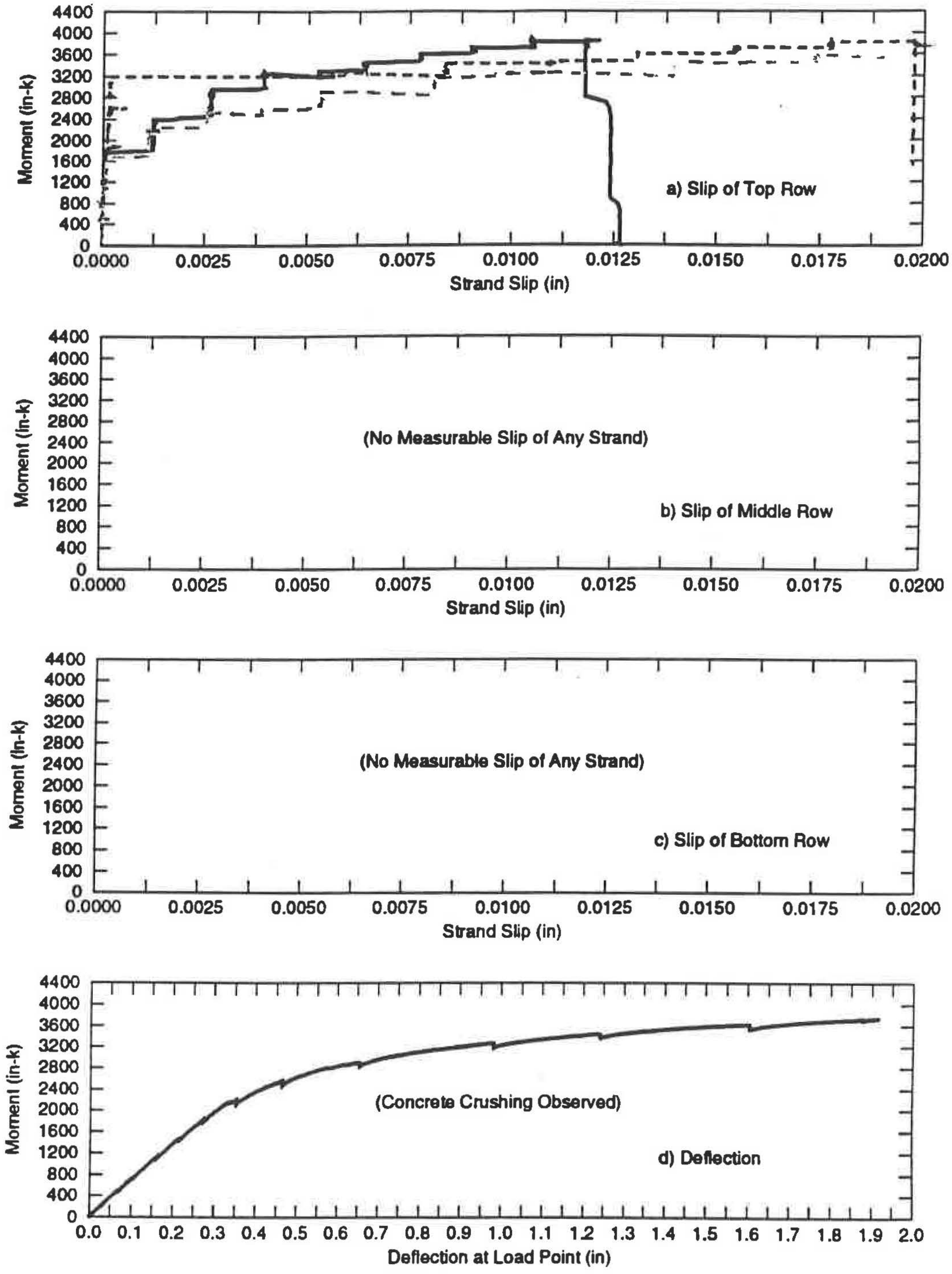


Figure C-7. Flexural Test Data for Test 7. (Beam 4, End B, 1.75 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

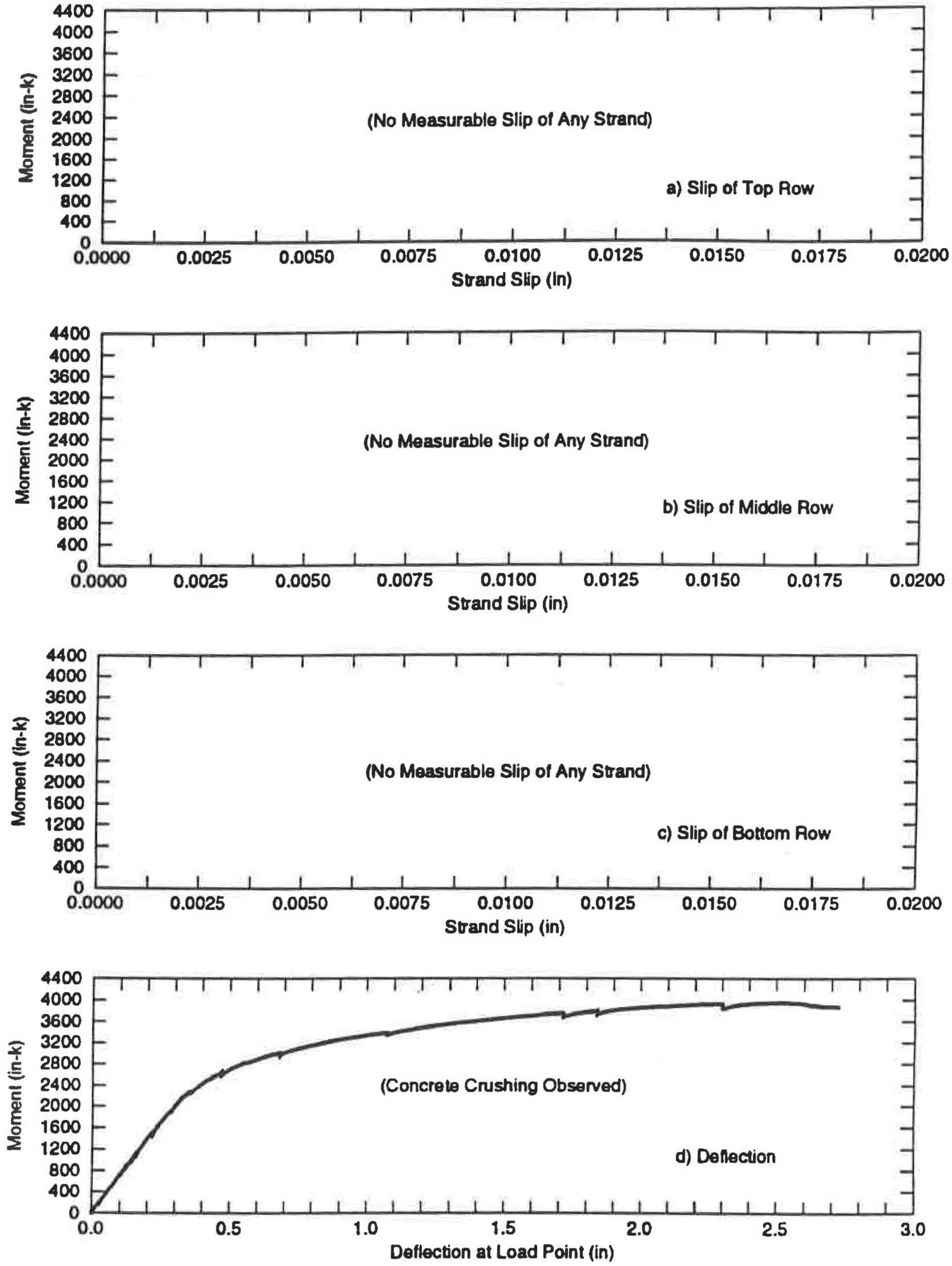


Figure C-8. Flexural Test Data for Test 8. (Beam 5, End A, 1.75 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 150 Inch Embedment Length, Flexural Failure.)

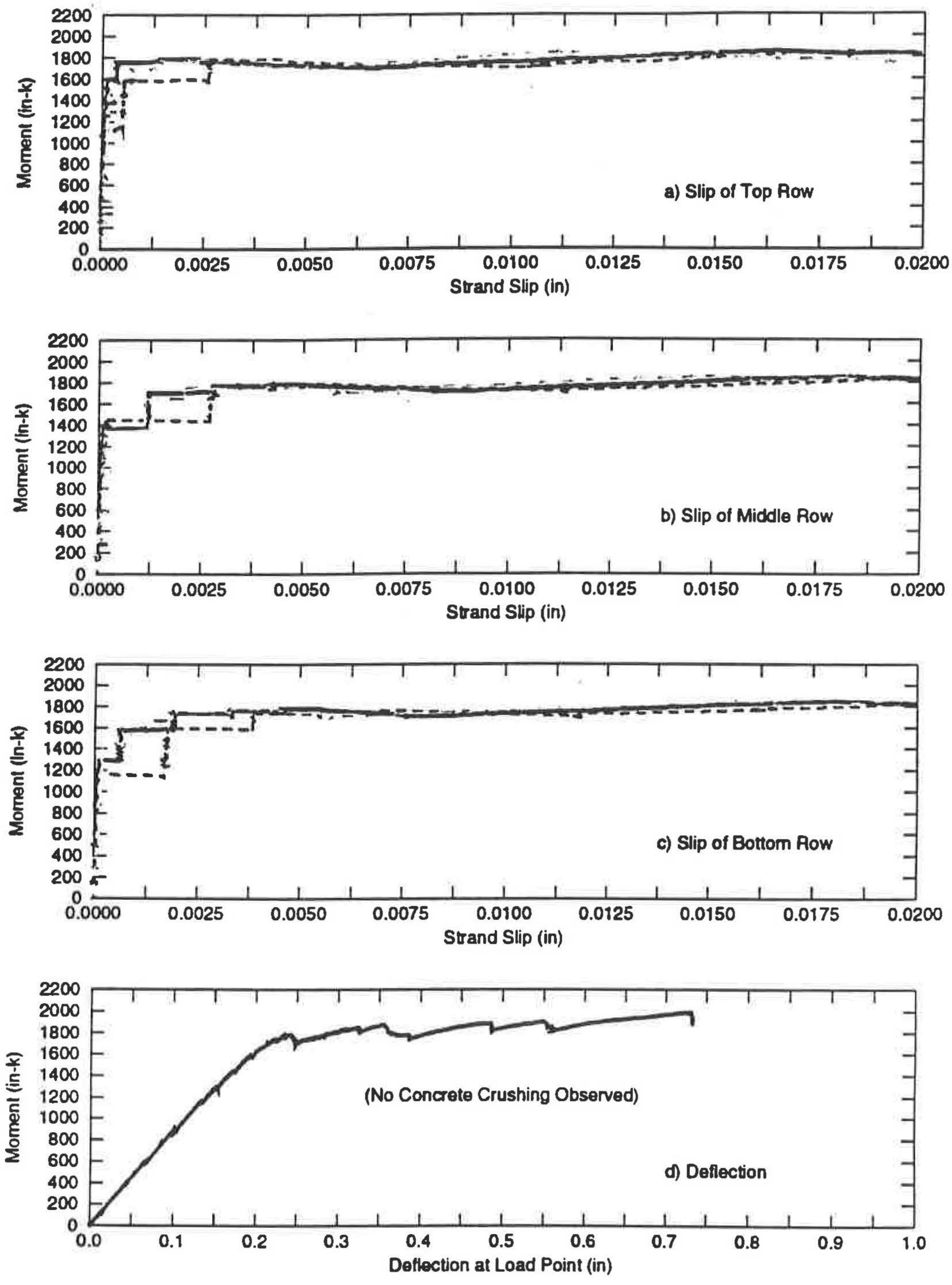


Figure C-9. Flexural Test Data for Test 9. (Beam 7, End A, 2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 96 Inch Embedment Length, Bond Failure.)

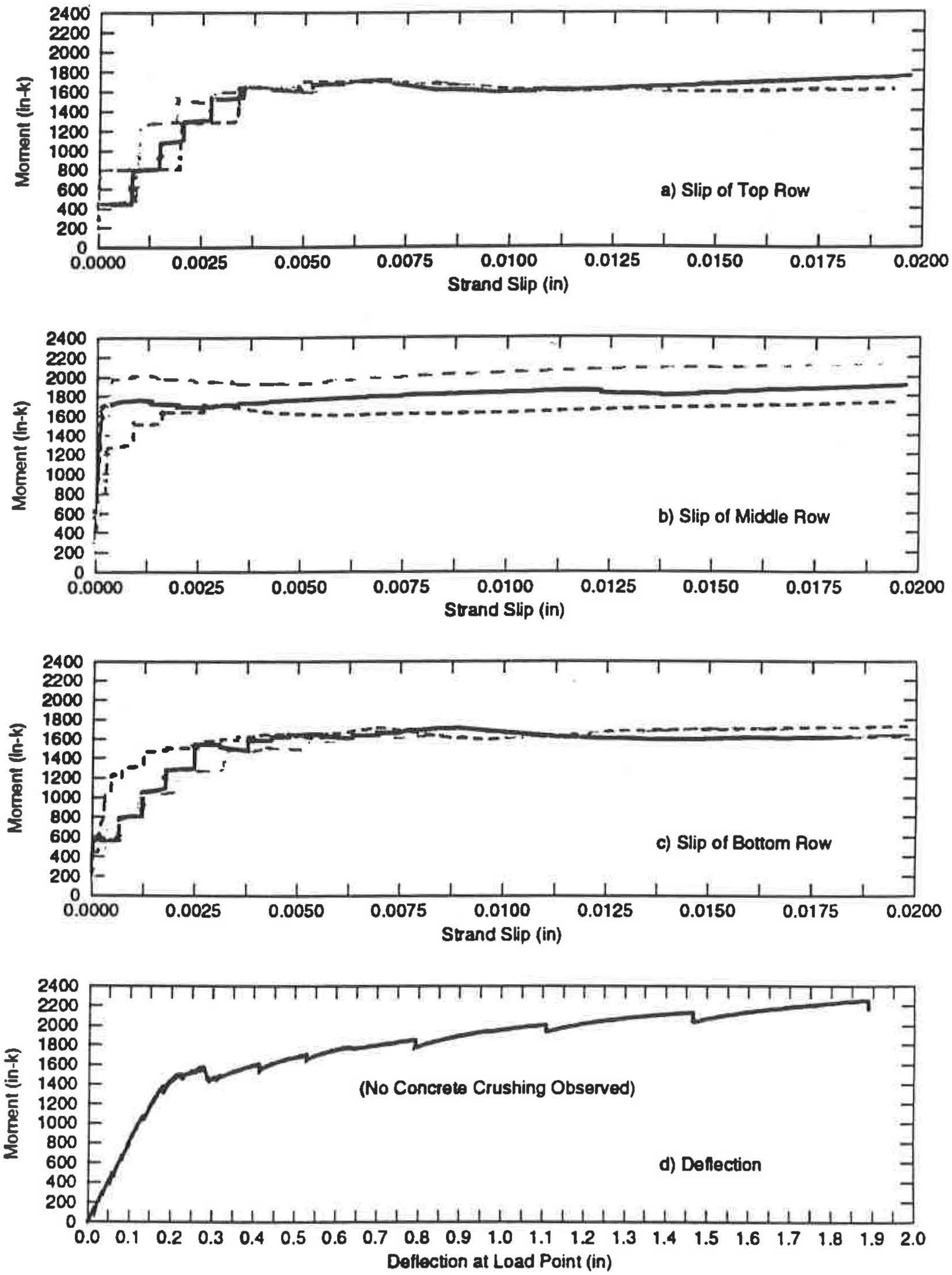


Figure C-10. Flexural Test Data for Test 10. (Beam 8, End A, 2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 114 Inch Embedment Length, Bond Failure.)

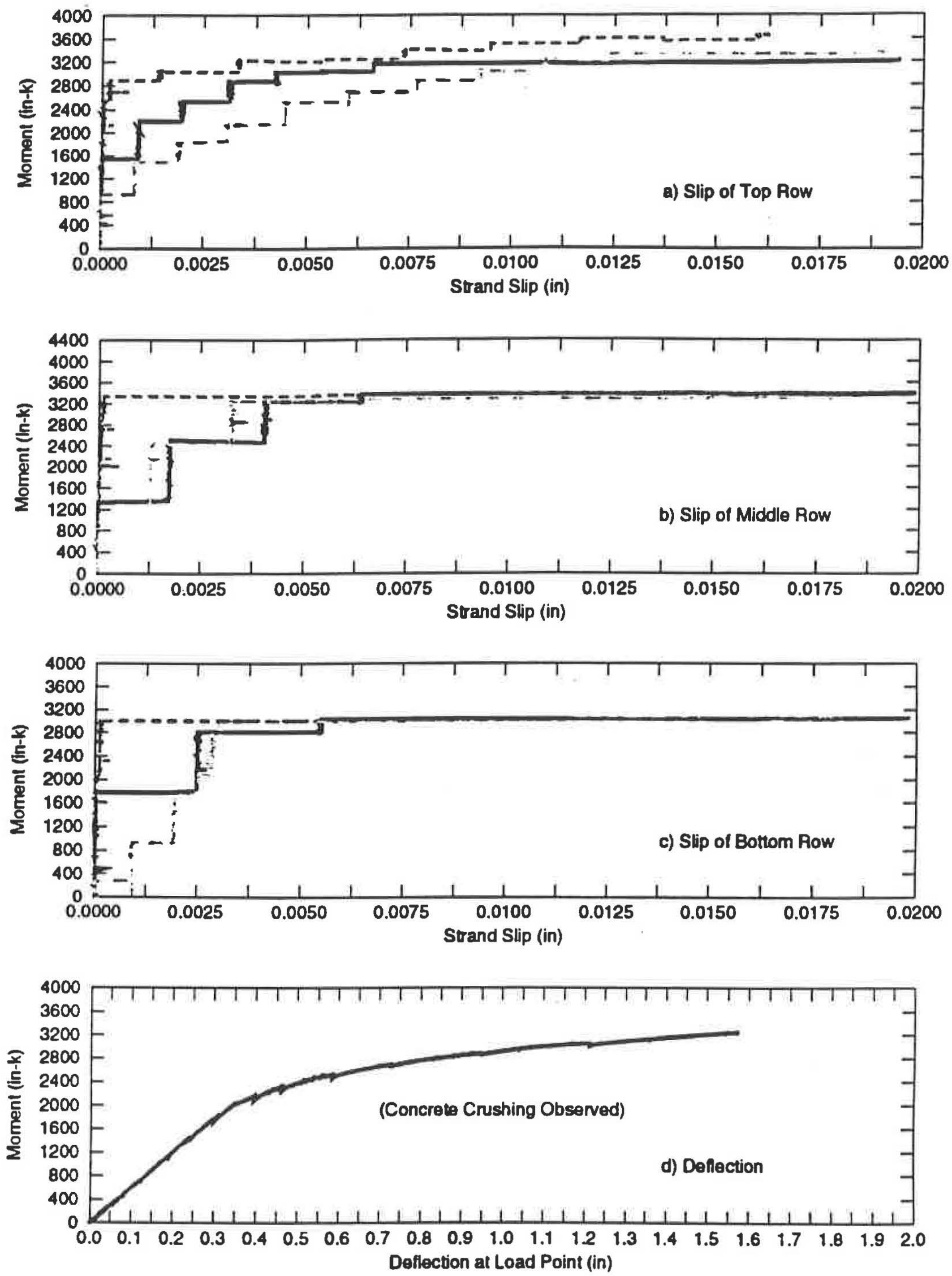


Figure C-11. Flexural Test Data for Test 11. (Beam 9, End A, 2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

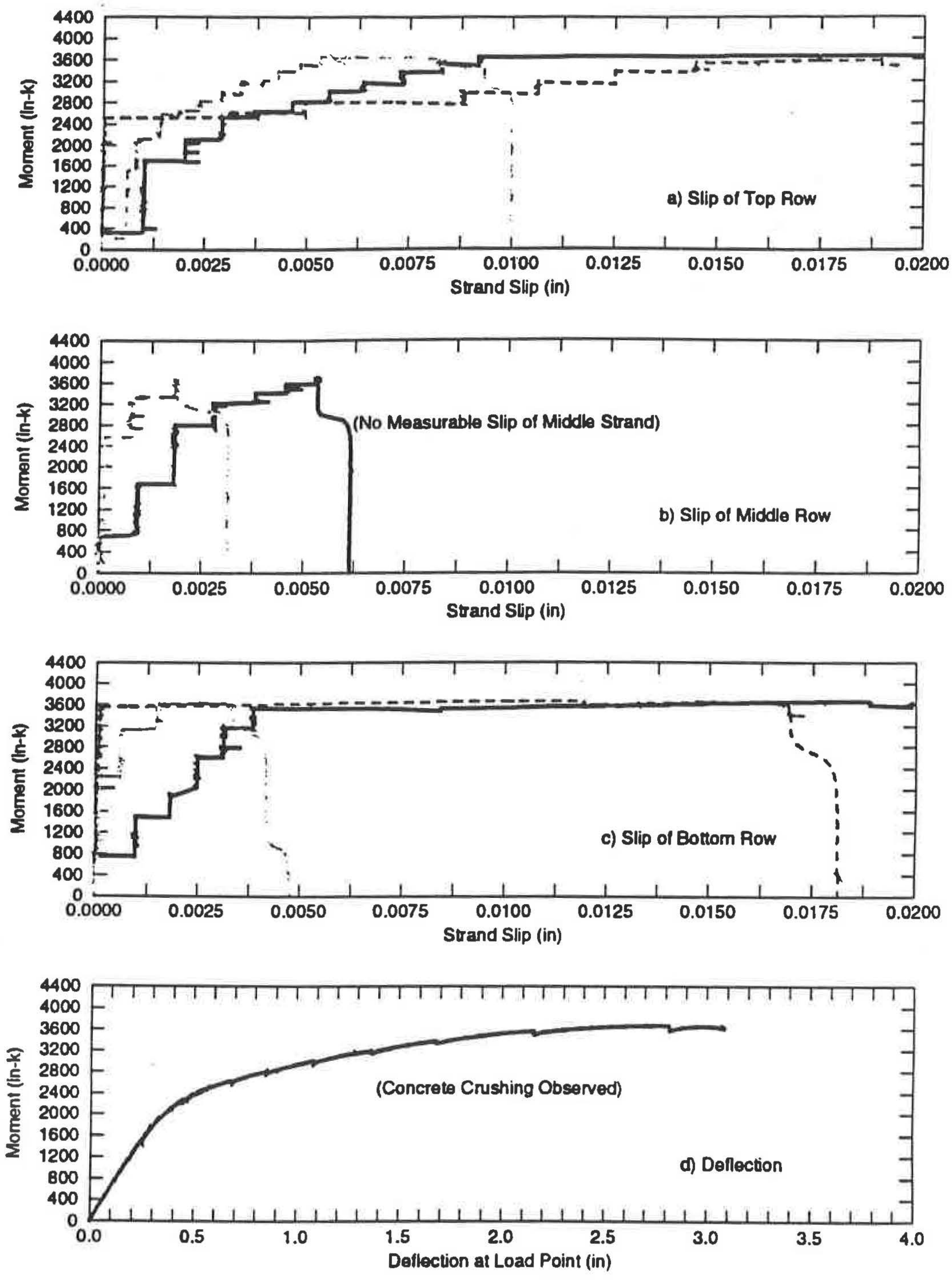


Figure C-12. Flexural Test Data for Test 12. (Beam 9, End B, 2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

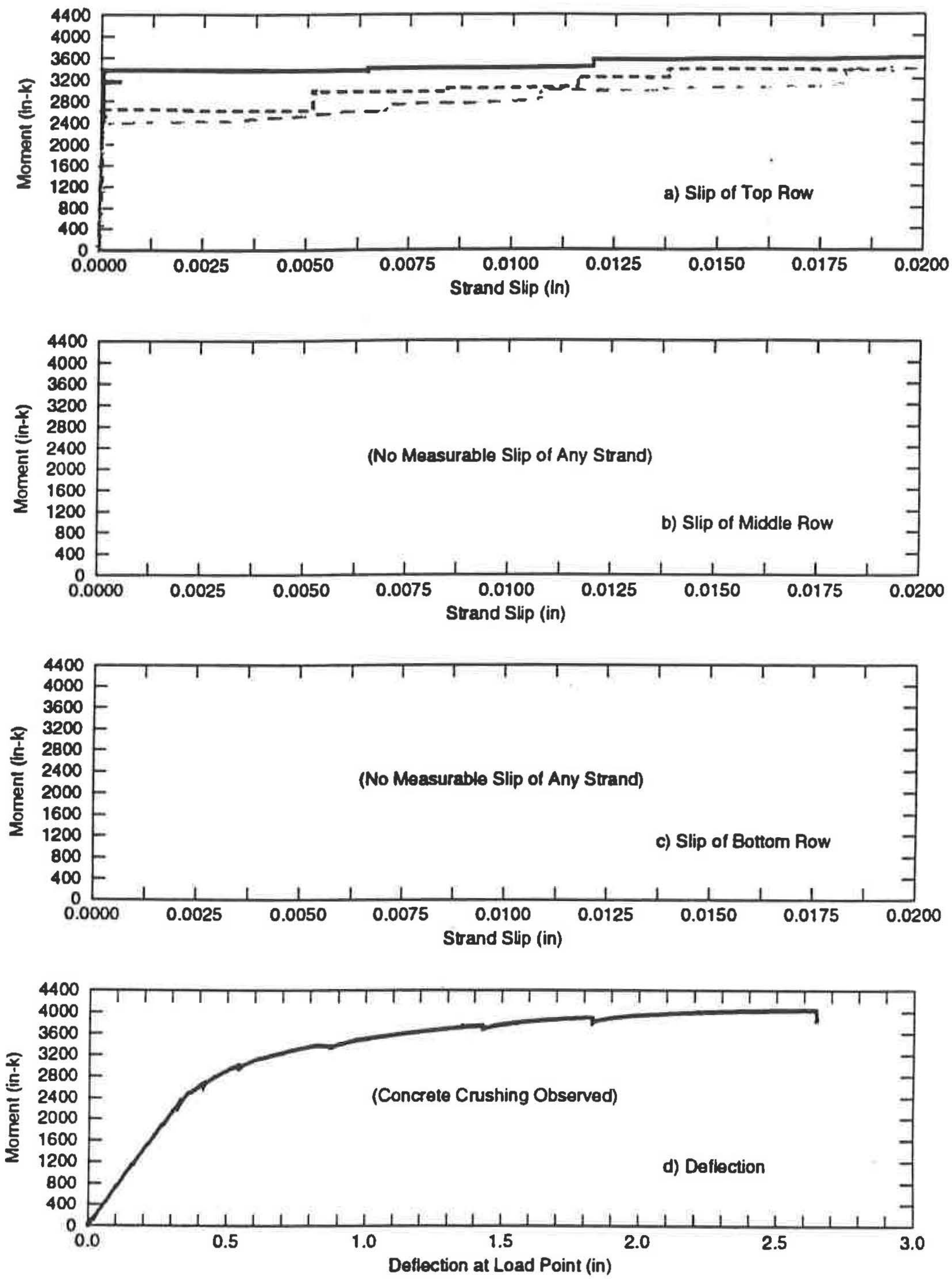


Figure C-13. Flexural Test Data for Test 13. (Beam 12, End B, 2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

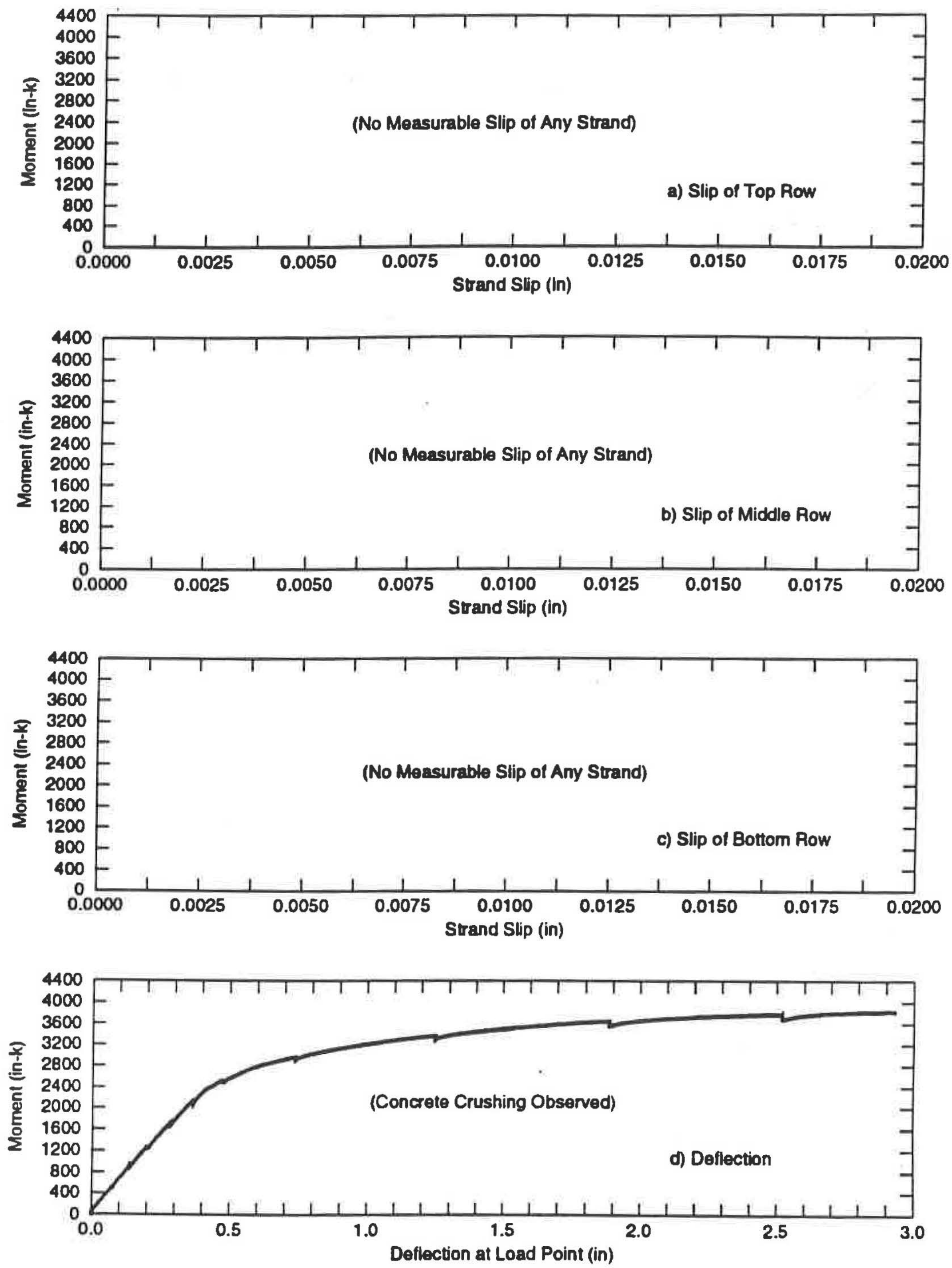


Figure C-14. Flexural Test Data for Test 14. (Beam 12, End A, 2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 168 Inch Embedment Length, Flexural Failure.)

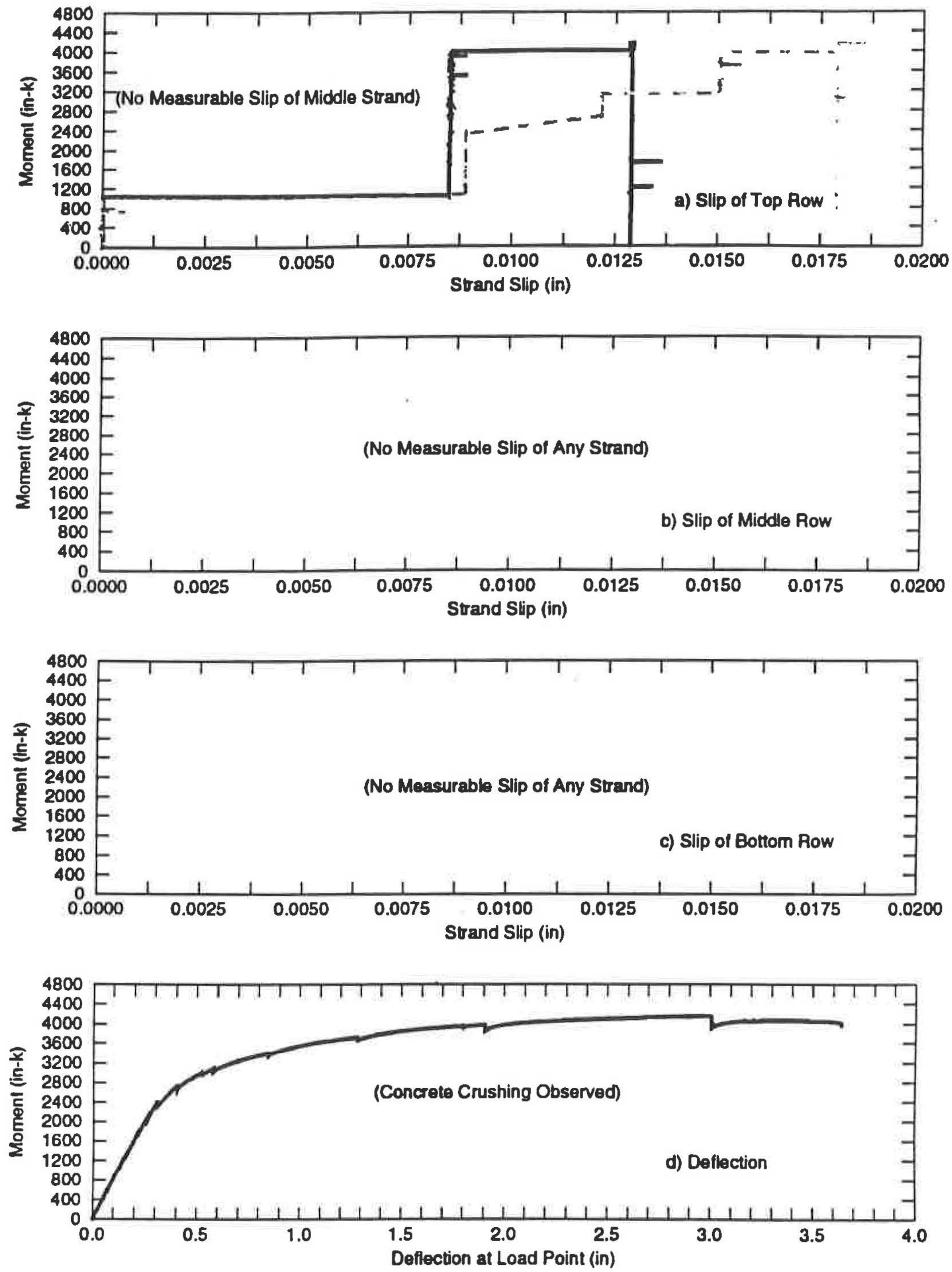


Figure C-15. Flexural Test Data for Test 15. (Beam 10, End A, 2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 108 Inch Embedment Length, Flex/Slip Failure.)

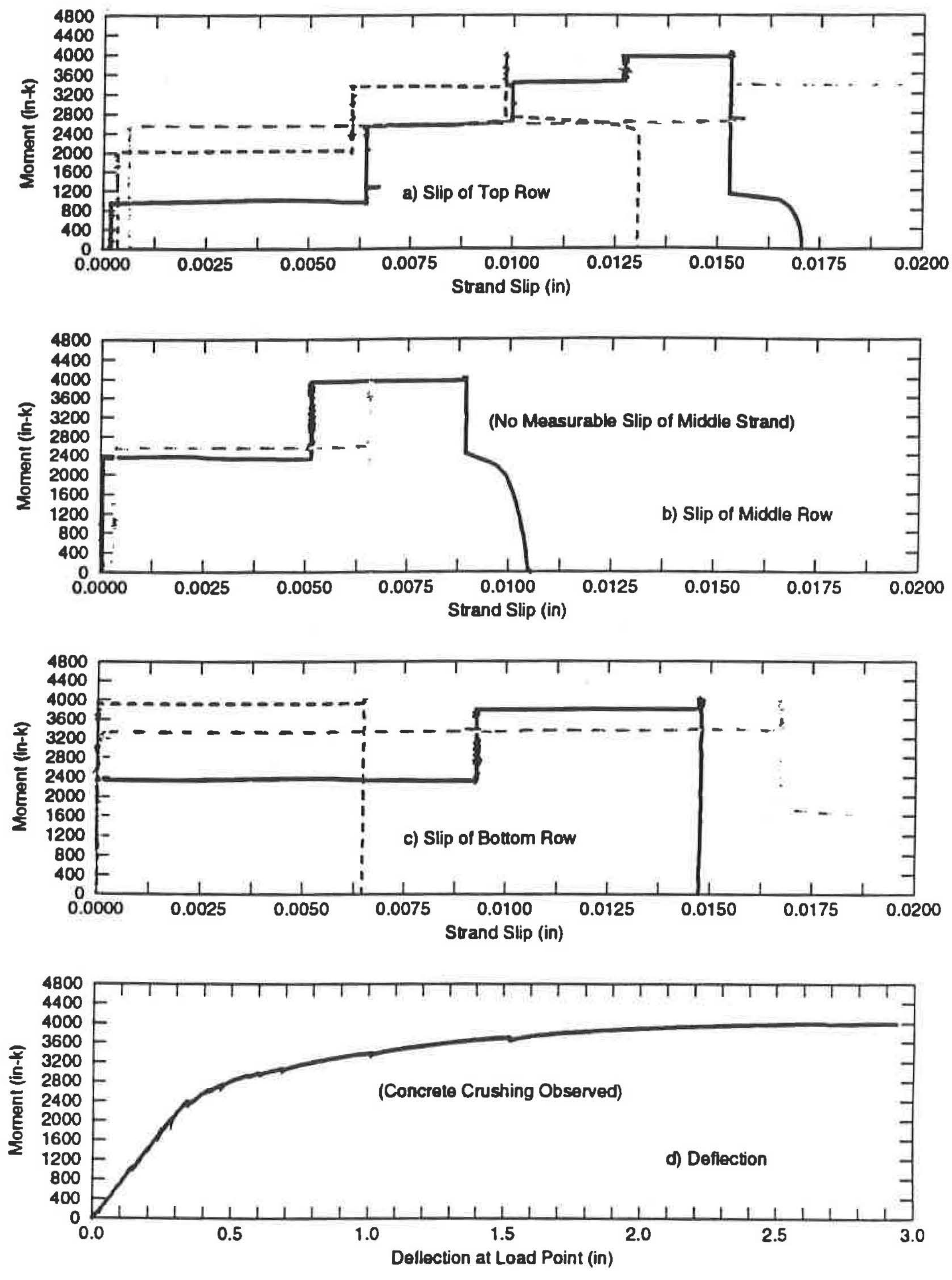


Figure C-16. Flexural Test Data for Test 16. (Beam 11, End B, 2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 108 Inch Embedment Length, Flex/Slip Failure.)

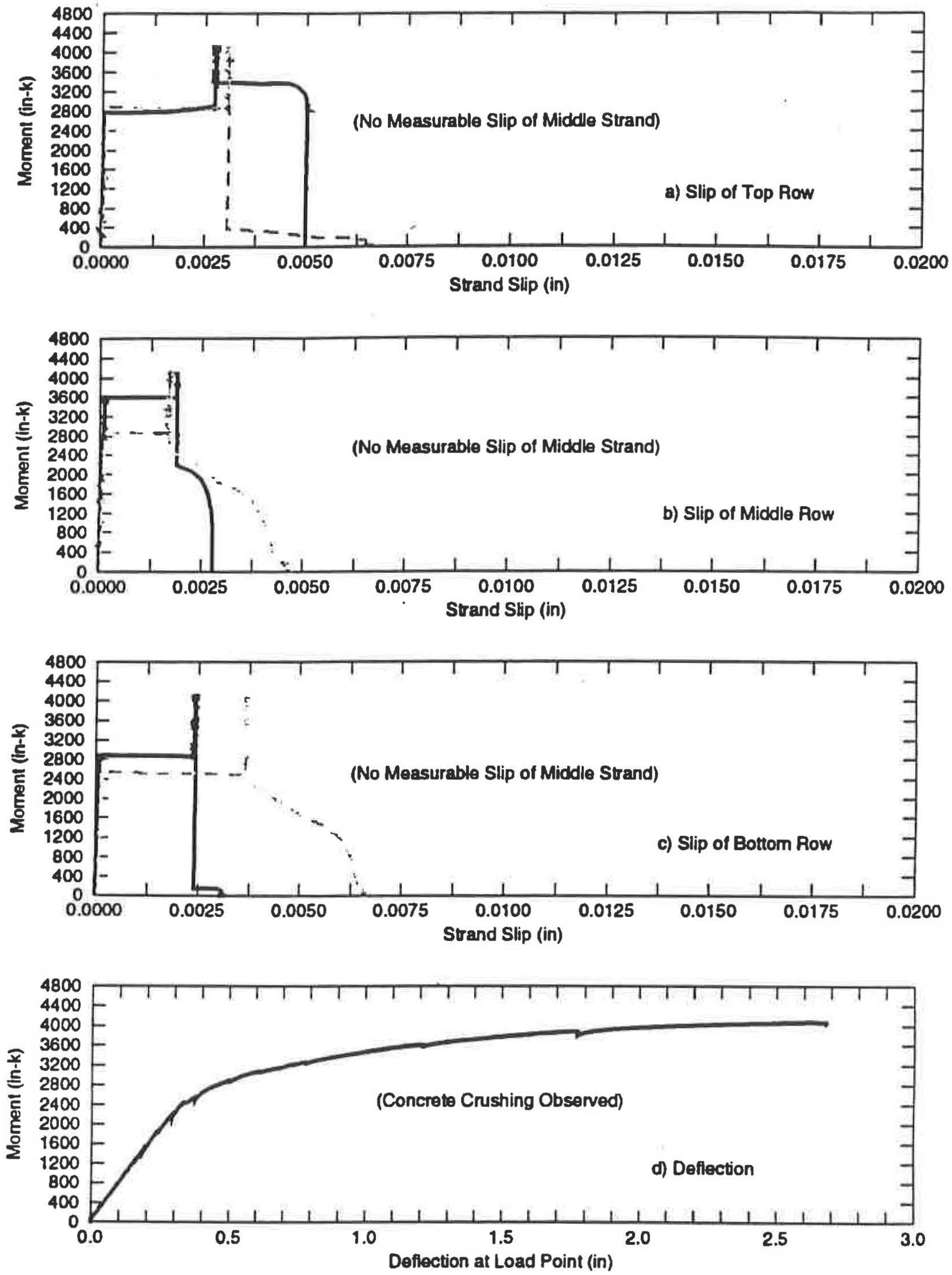


Figure C-17. Flexural Test Data for Test 17. (Beam 11, End A, 2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flexural Failure.)

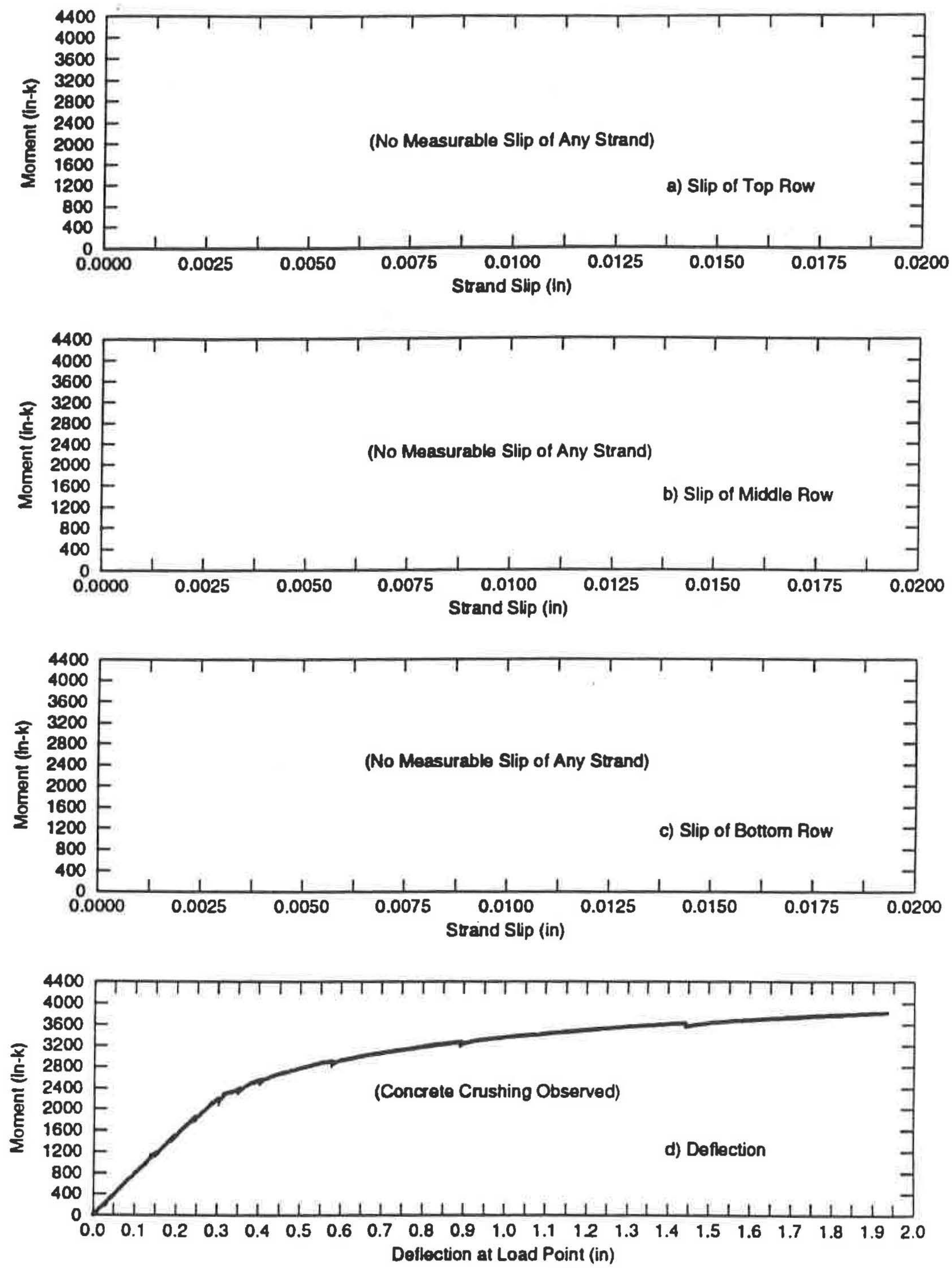


Figure C-18. Flexural Test Data for Test 18. (Beam 10, End B, 2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flexural Failure.)

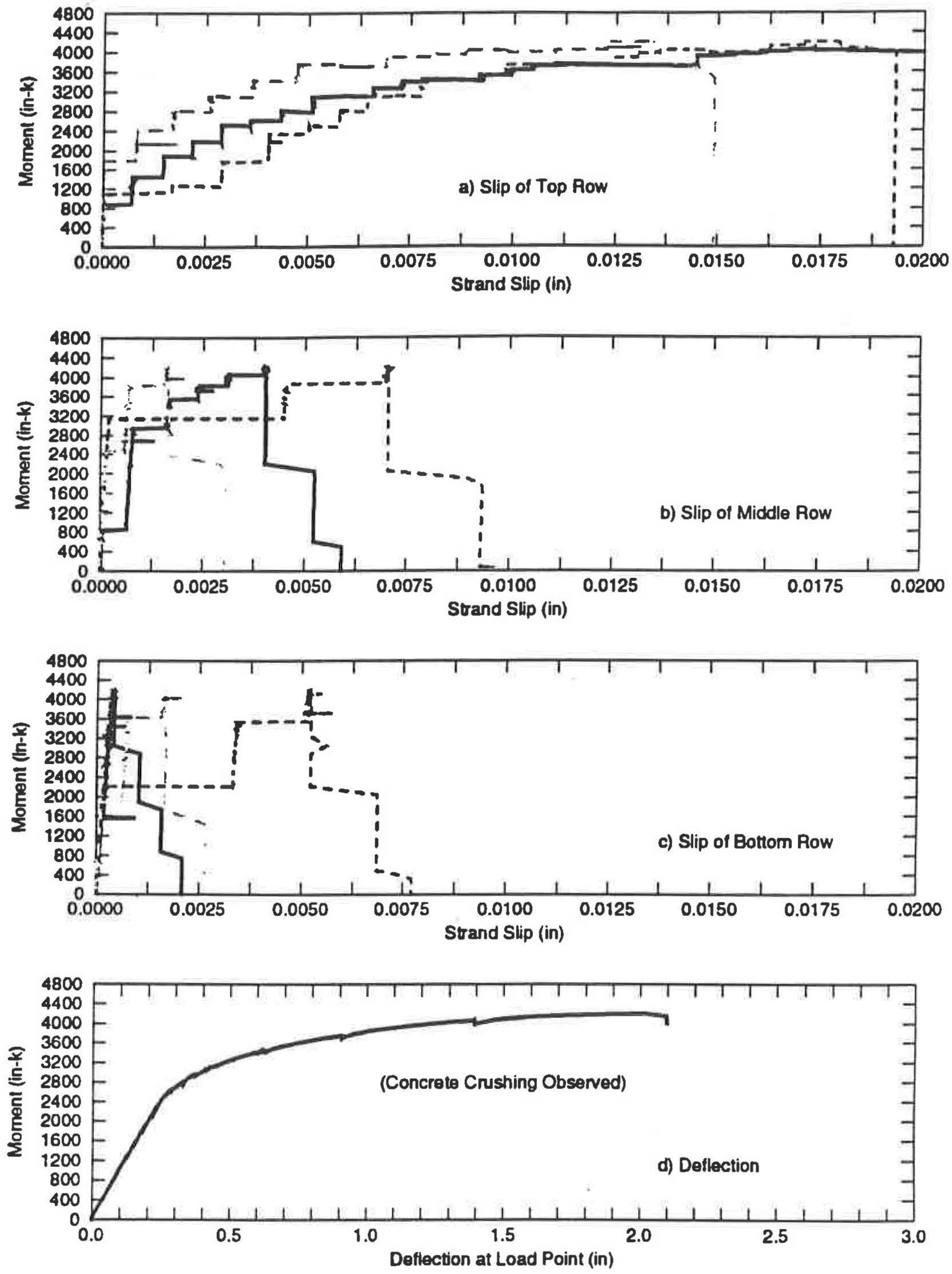


Figure C-20. Flexural Test Data for Test 20. (Beam 13, End B, 1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 114 Inch Embedment Length, Flex/Slip Failure.)

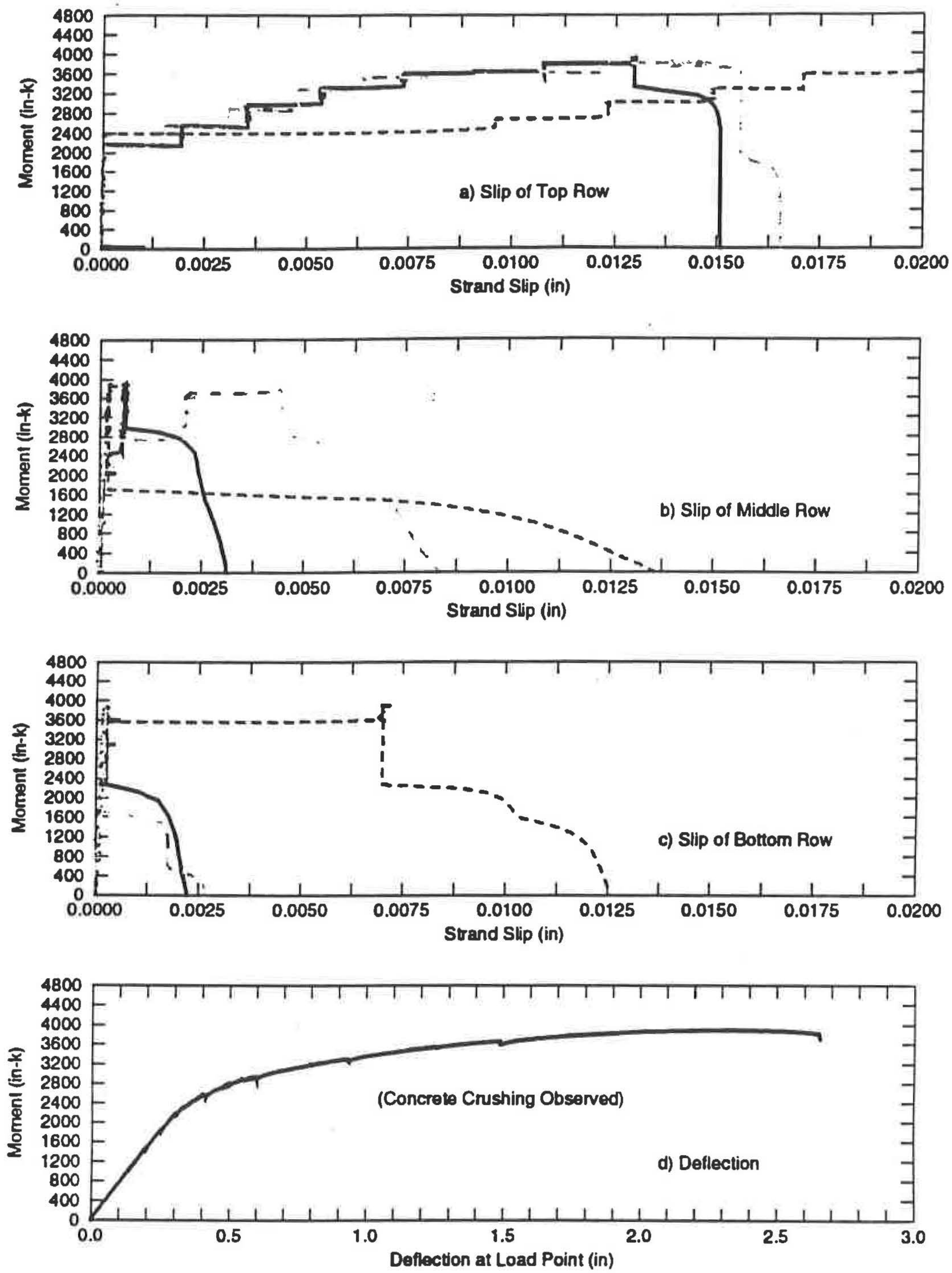


Figure C-21. Flexural Test Data for Test 21. (Beam 13, End A, 1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 126 Inch Embedment Length, Flex/Slip Failure.)

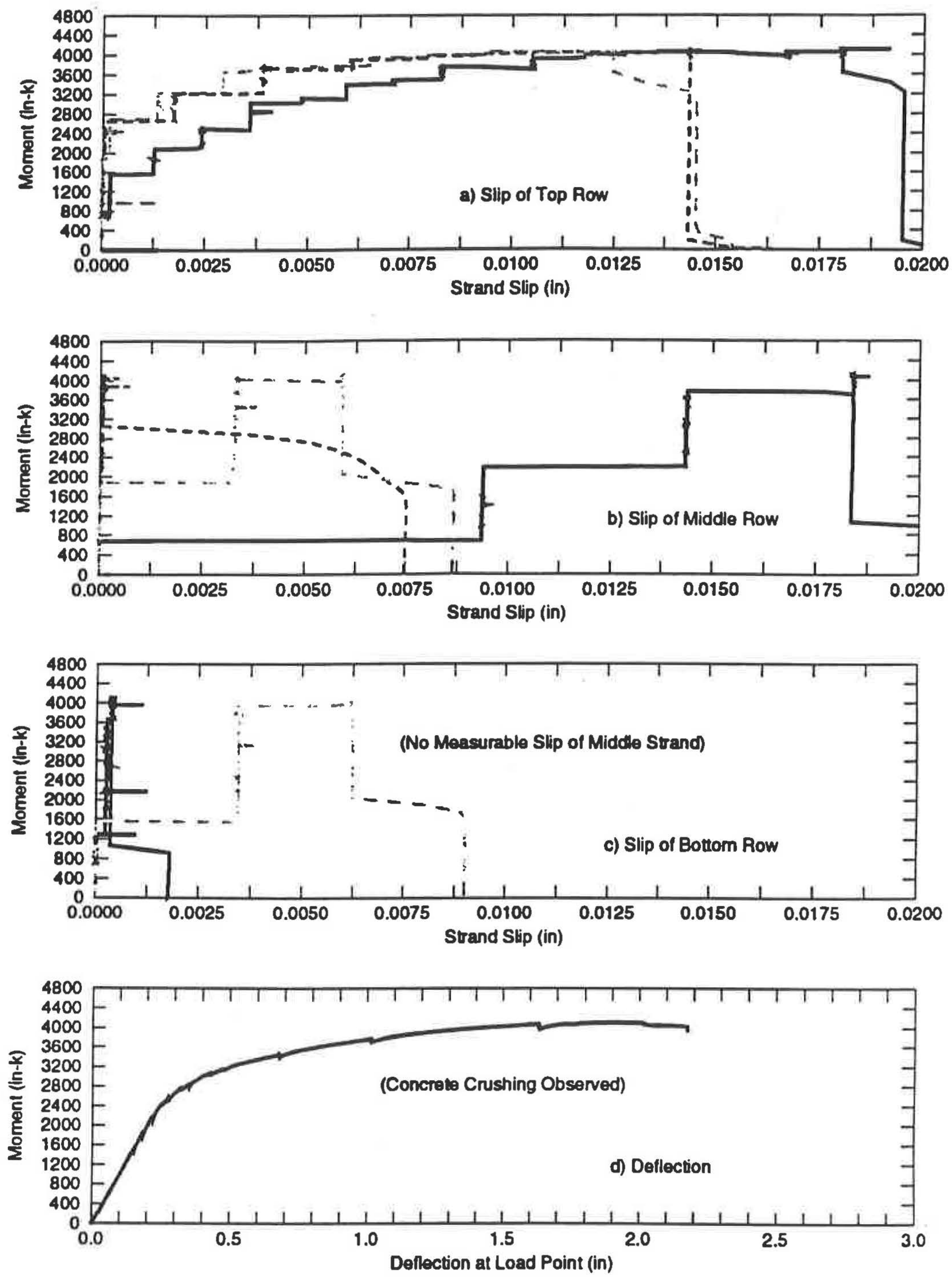


Figure C-22. Flexural Test Data for Test 22. (Beam 14, End B, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 114 Inch Embedment Length, Flex/Slip Failure.)

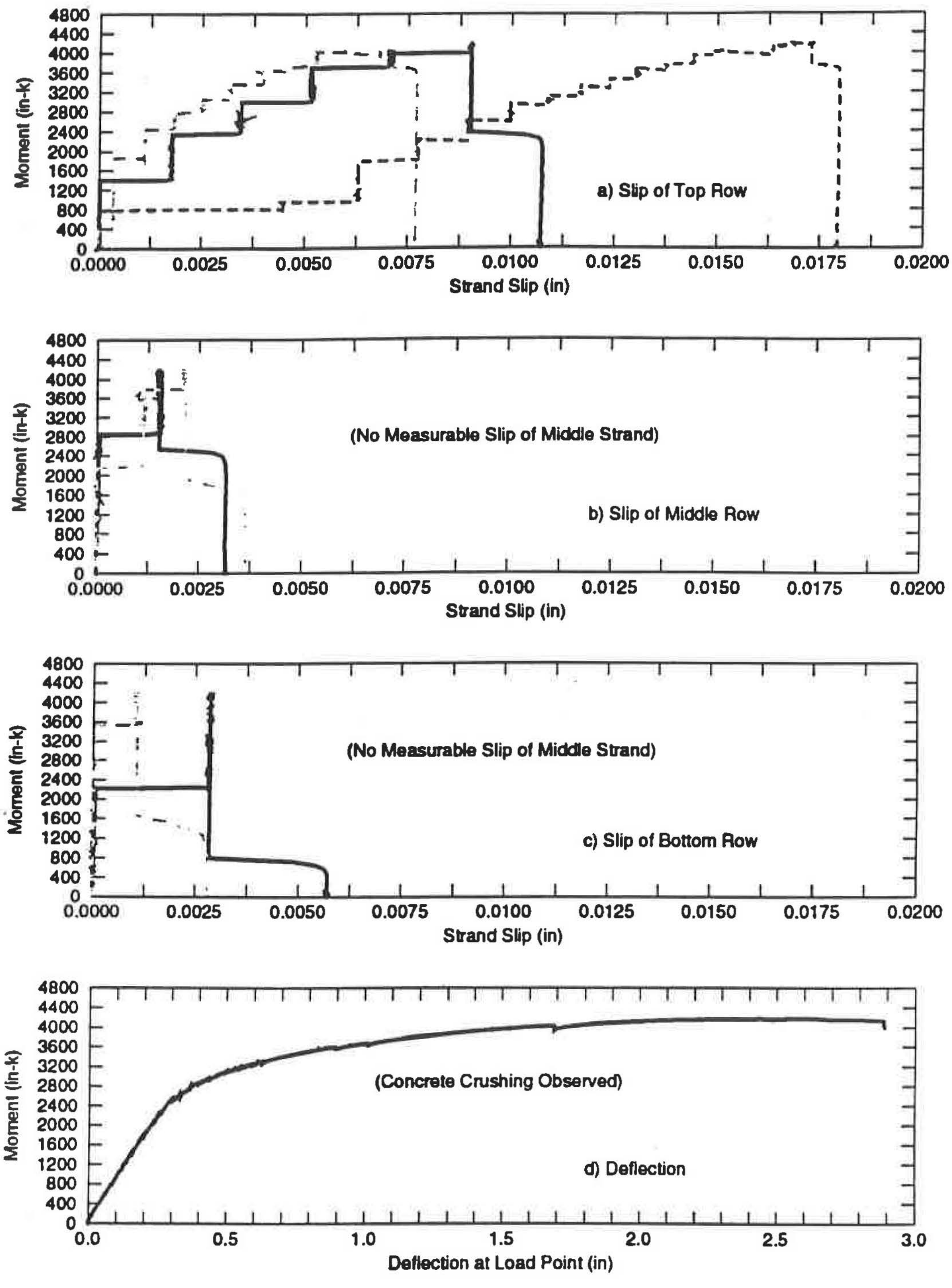


Figure C-23. Flexural Test Data for Test 23. (Beam 14, End A, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 126 Inch Embedment Length, Flex/Slip Failure.)

APPENDIX D

D. BEAM CRACKING DURING FLEXURAL TESTS

The cracking diagrams in Appendix D show all cracking and crushing of concrete for each flexural test performed. Each figure shows both sides of the end of the beam being tested. On each figure the embedment length (distance from the end of the beam being tested to the point of load) is labeled. The distance from the end of the beam to the nearest crack to the end of the beam is also labeled. The figures are not to scale.

Each figure number coincides with the test number of the flexural test performed. The figure titles include the important information about each test: beam number and end being tested, strand spacing, pour number and concrete strength category of the beam, confinement information, embedment length, and failure mode.

No data is available for test 19 due to problems with the data acquisition unit.

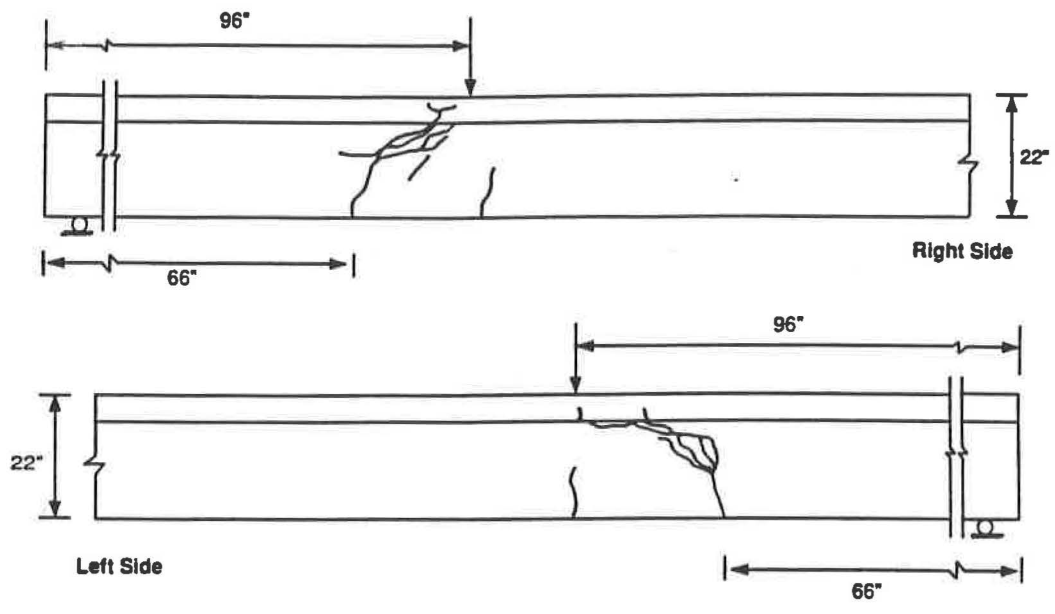


Figure D-1. Crack Diagrams for Test 1. (Beam 2, End A, 1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 96 Inch Embedment Length, Bond Failure.)

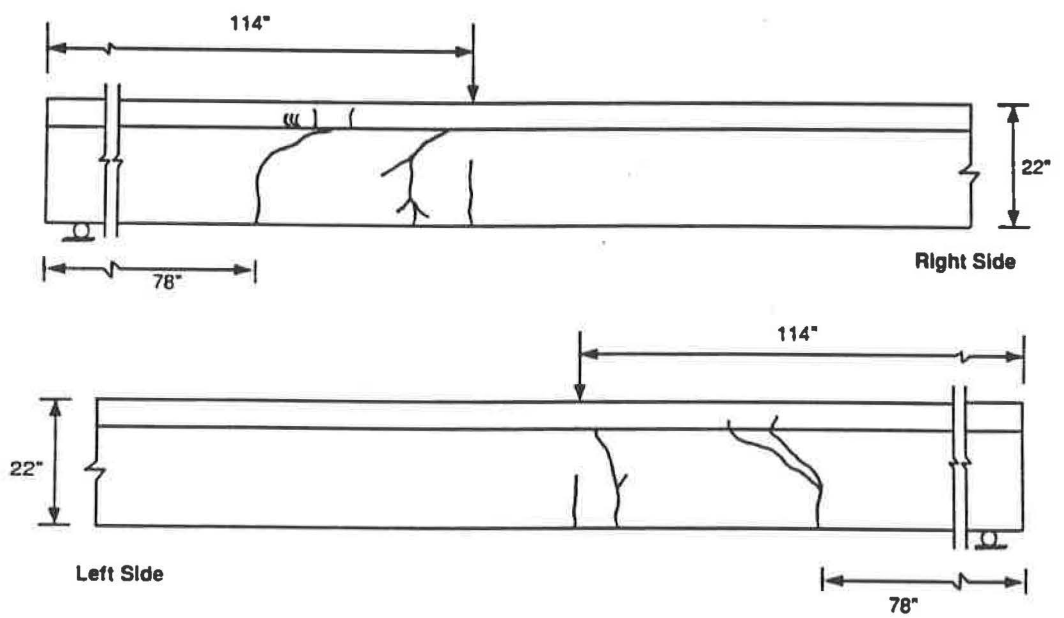


Figure D-2. Crack Diagrams for Test 2. (Beam 1, End A, 1.75 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 114 Inch Embedment Length, Bond Failure.)

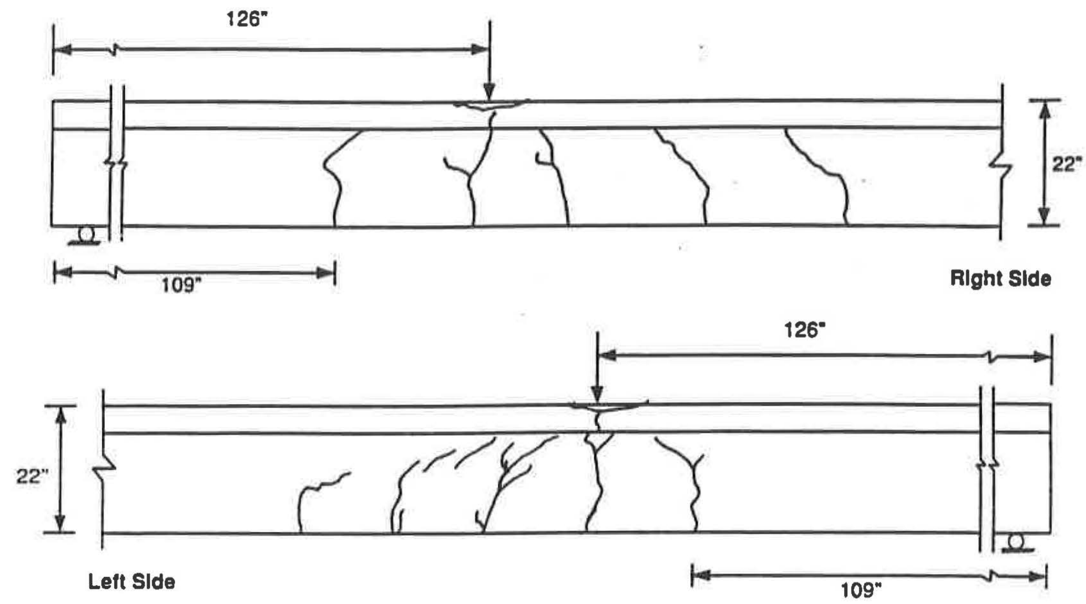


Figure D-3. Crack Diagrams for Test 3. (Beam 3, End B, 1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

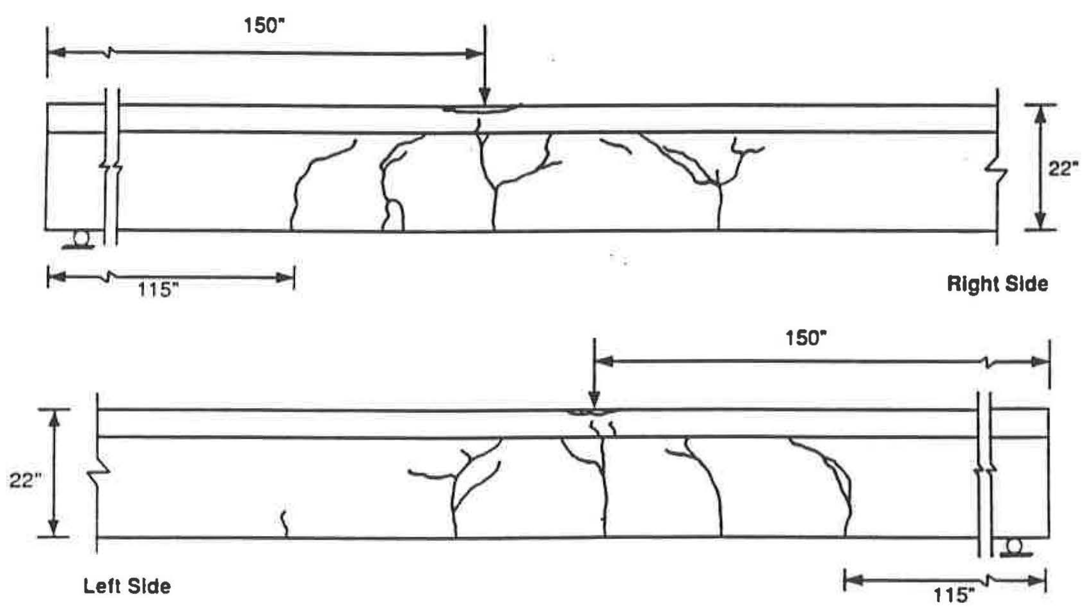


Figure D-4. Crack Diagrams for Test 4. (Beam 3, End A, 1.75 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

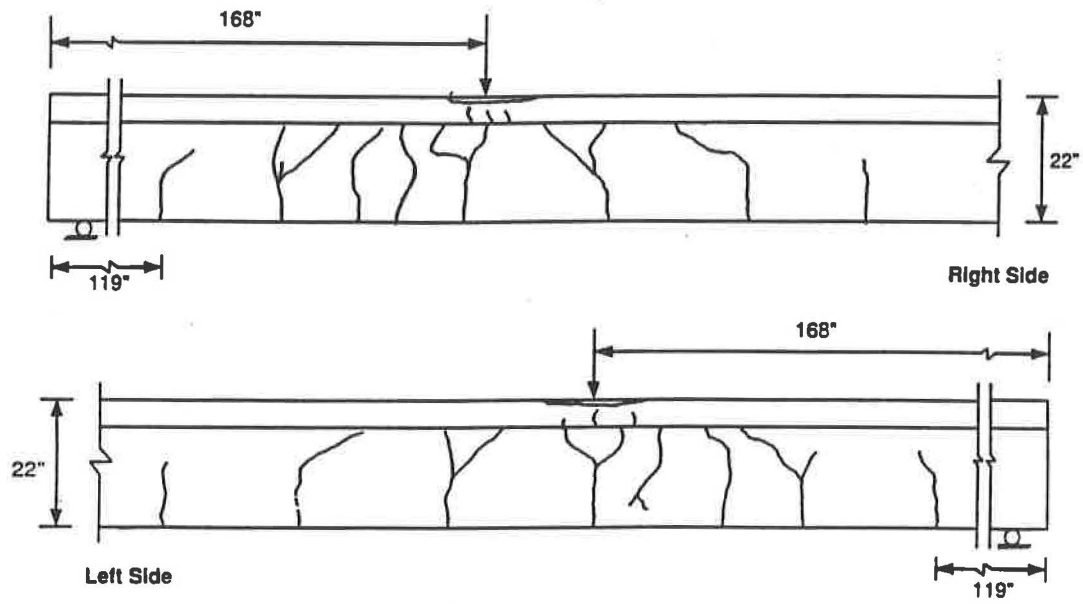


Figure D-5. Crack Diagrams for Test 5. (Beam 6, End A, 1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 168 Inch Embedment Length, Flex/Slip Failure.)

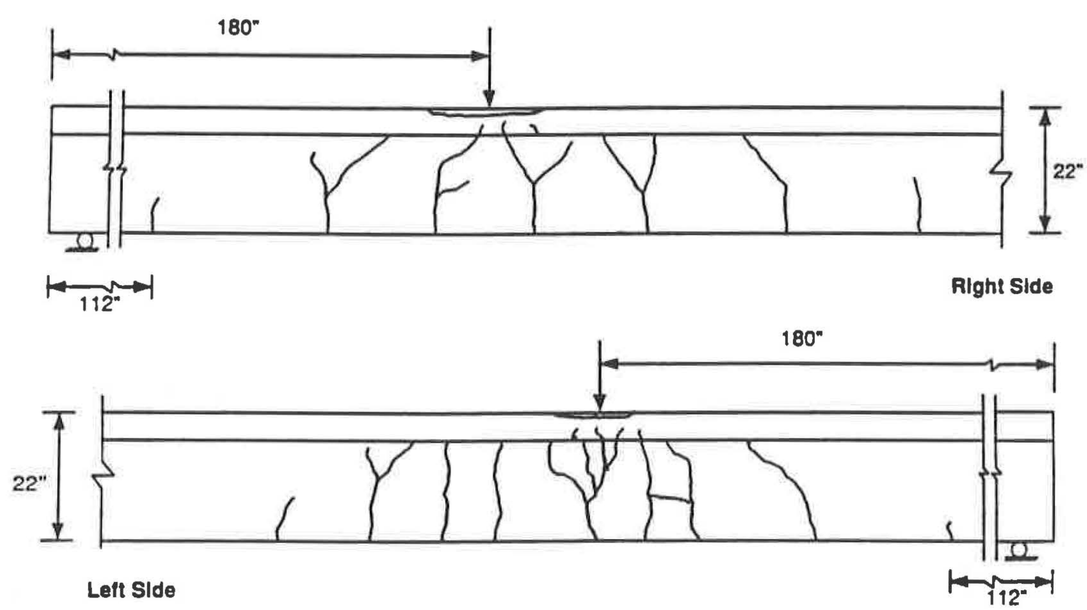


Figure D-6. Crack Diagrams for Test 6. (Beam 6, End B, 1.75 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 180 Inch Embedment Length, Flex/Slip Failure.)

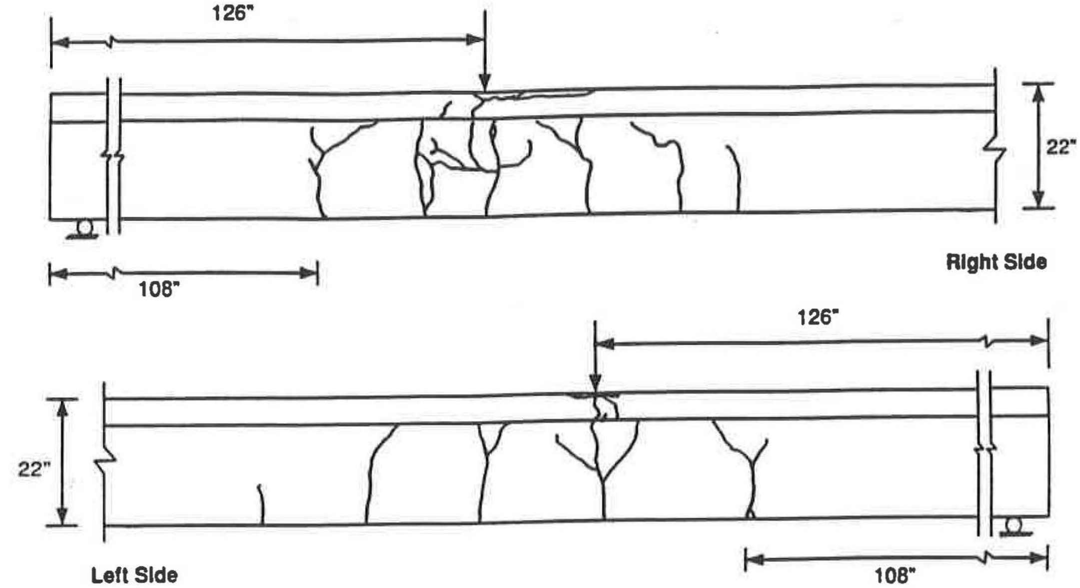


Figure D-7. Crack Diagrams for Test 7. (Beam 4, End B, 1.75 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

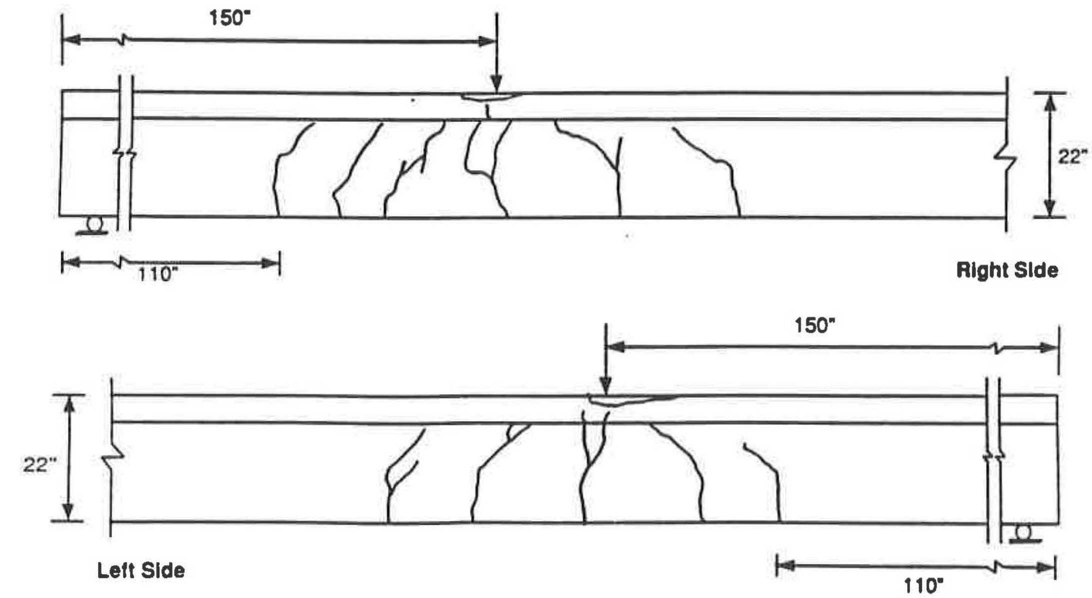


Figure D-8. Crack Diagrams for Test 8. (Beam 5, End A, 1.75 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 150 Inch Embedment Length, Flexural Failure.)

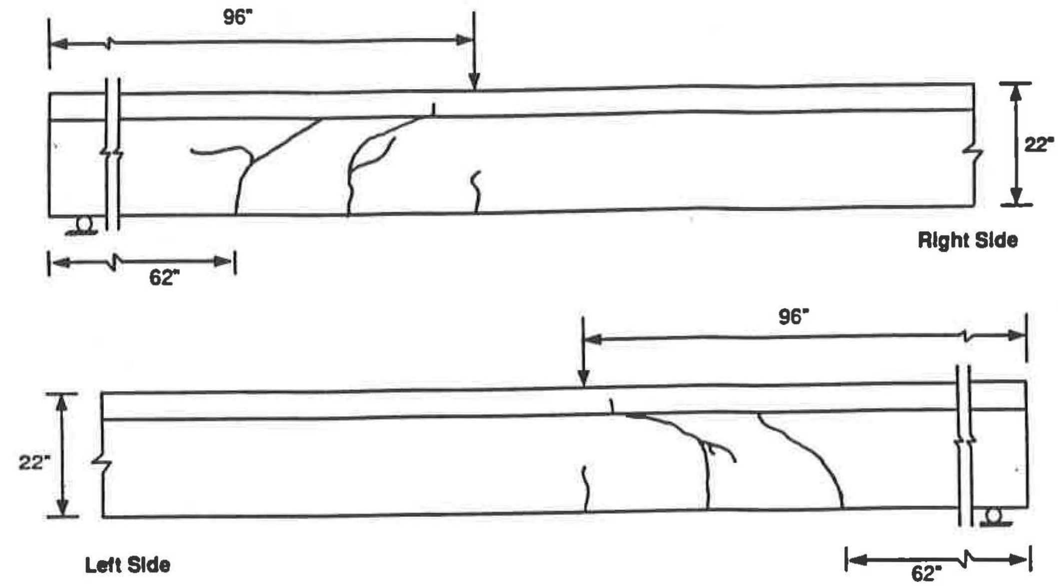


Figure D-9. Crack Diagrams for Test 9. (Beam 7, End A, 2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 96 Inch Embedment Length, Bond Failure.)

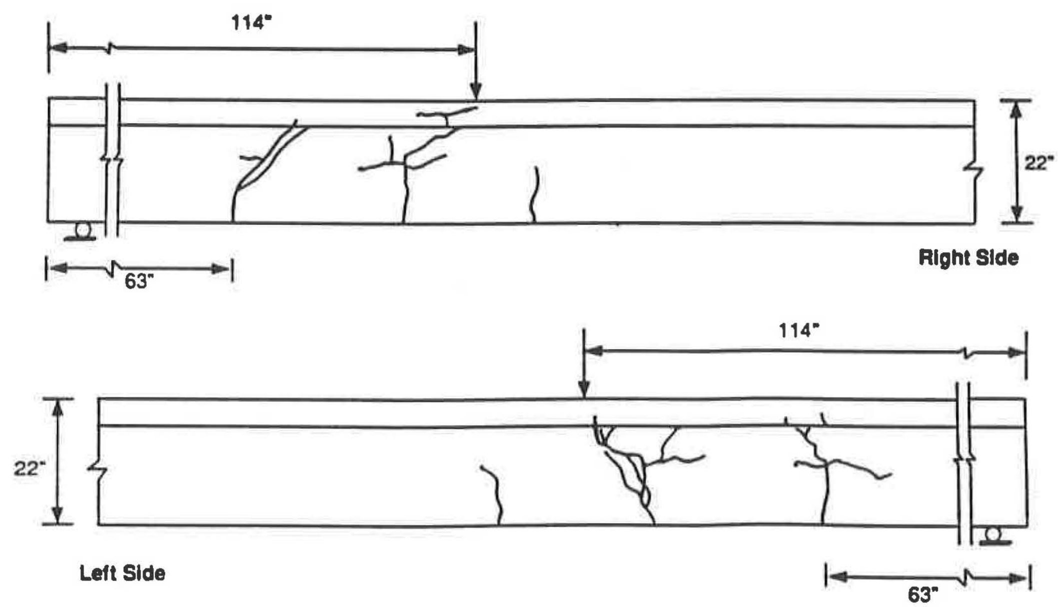


Figure D-10. Crack Diagrams for Test 10. (Beam 8, End A, 2.0 Inch Strand Spacing, Pour 1 - Normal Strength Mix, Unconfined, 114 Inch Embedment Length, Bond Failure.)

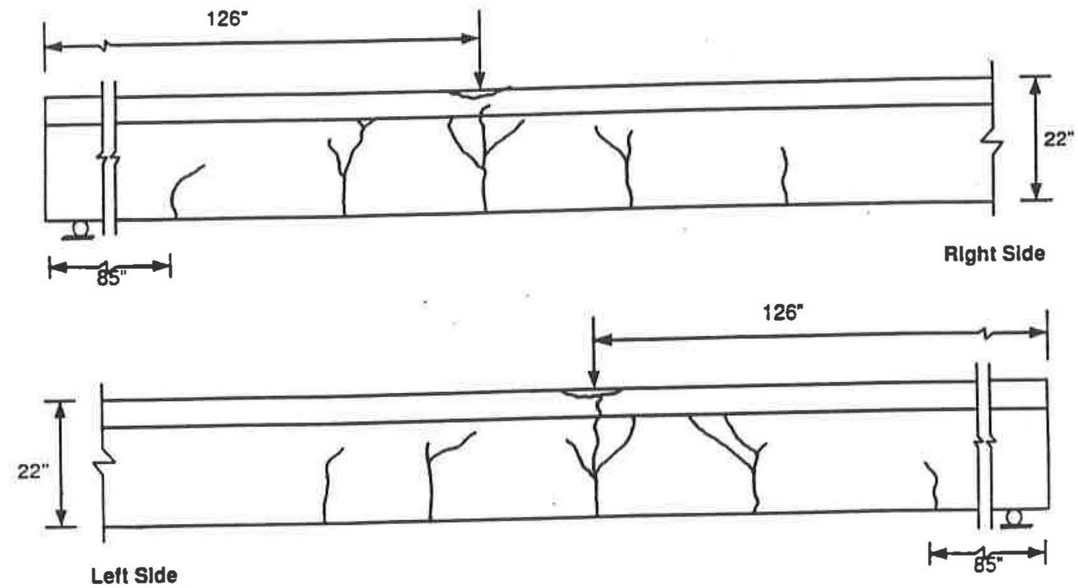


Figure D-11. Crack Diagrams for Test 11. (Beam 9, End A, 2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 126 Inch Embedment Length, Flex/Slip Failure.)

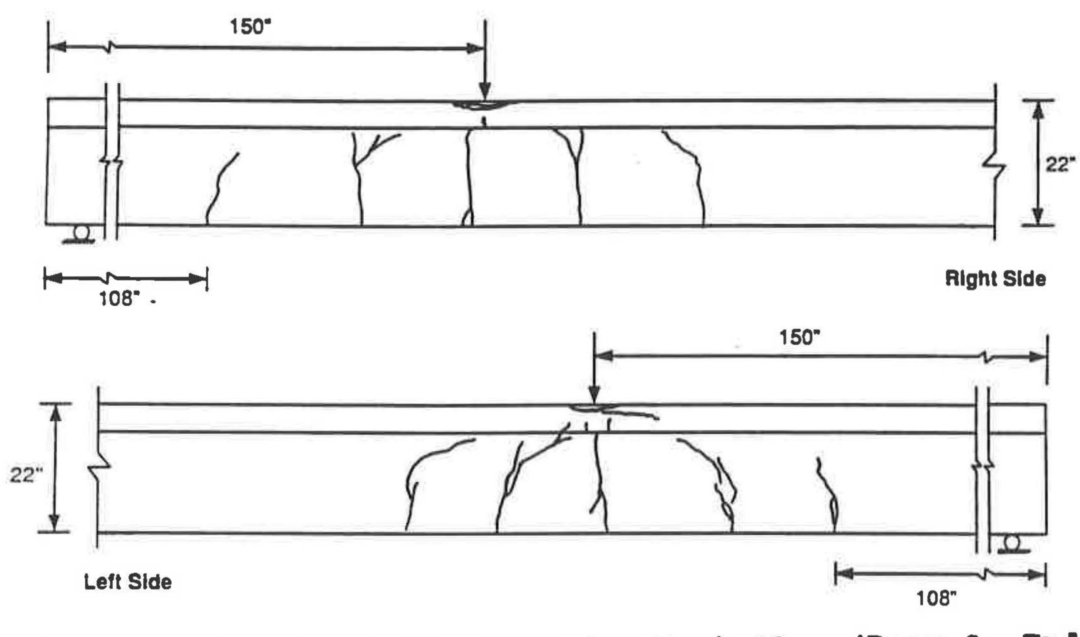


Figure D-12. Crack Diagrams for Test 12. (Beam 9, End B, 2.0 Inch Strand Spacing, Pour 2 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

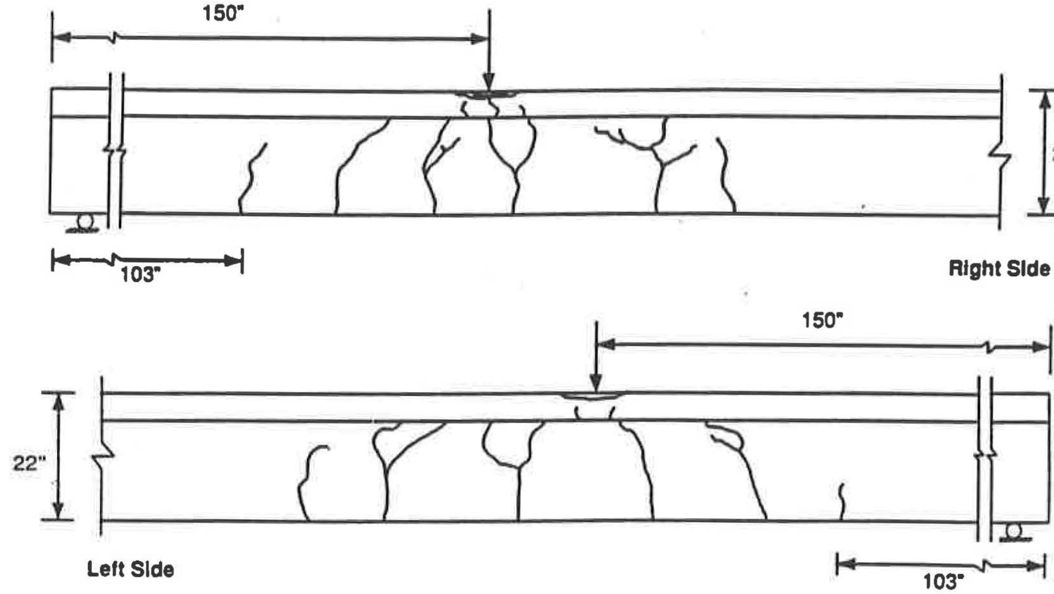


Figure D-13. Crack Diagrams for Test 13. (Beam 12, End B, 2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 150 Inch Embedment Length, Flex/Slip Failure.)

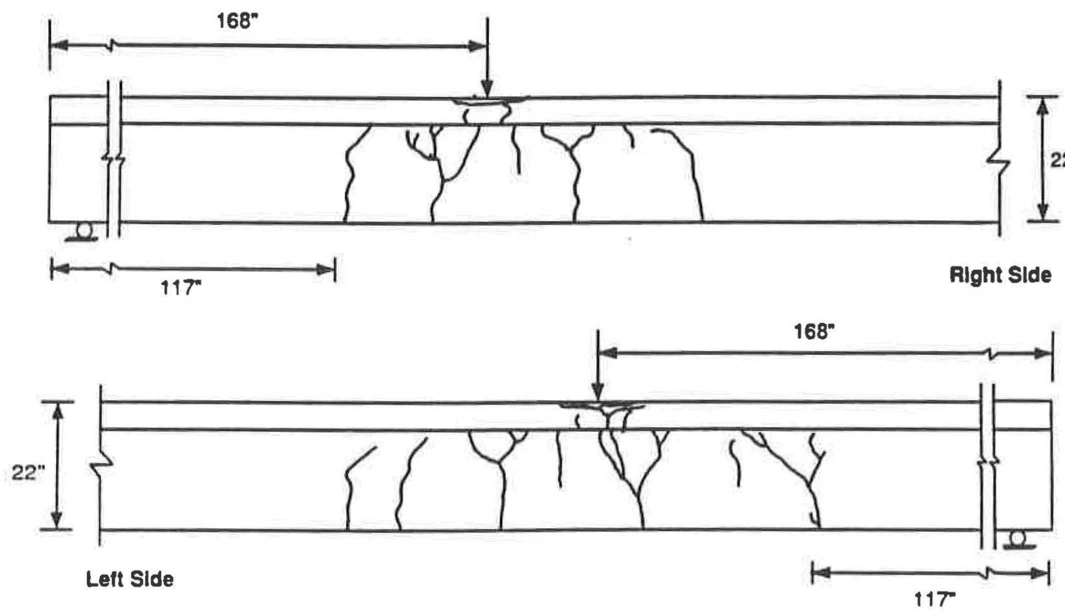


Figure D-14. Crack Diagrams for Test 14. (Beam 12, End A, 2.0 Inch Strand Spacing, Pour 5 - Normal Strength Mix, Unconfined, 168 Inch Embedment Length, Flexural Failure.)

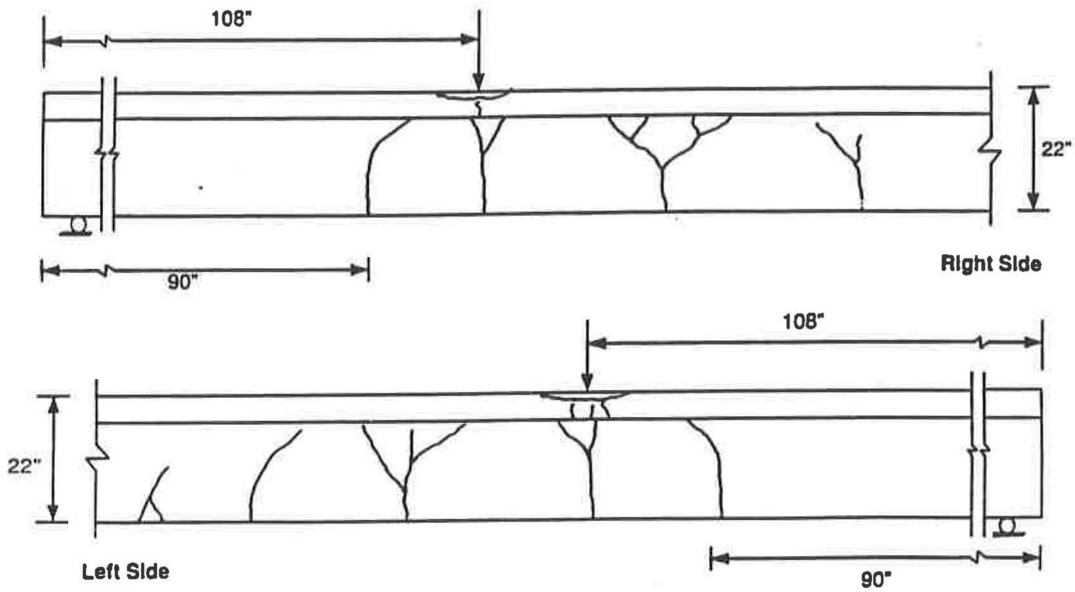


Figure D-15. Crack Diagrams for Test 15. (Beam 10, End A, 2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 108 Inch Embedment Length, Flex/Slip Failure.)

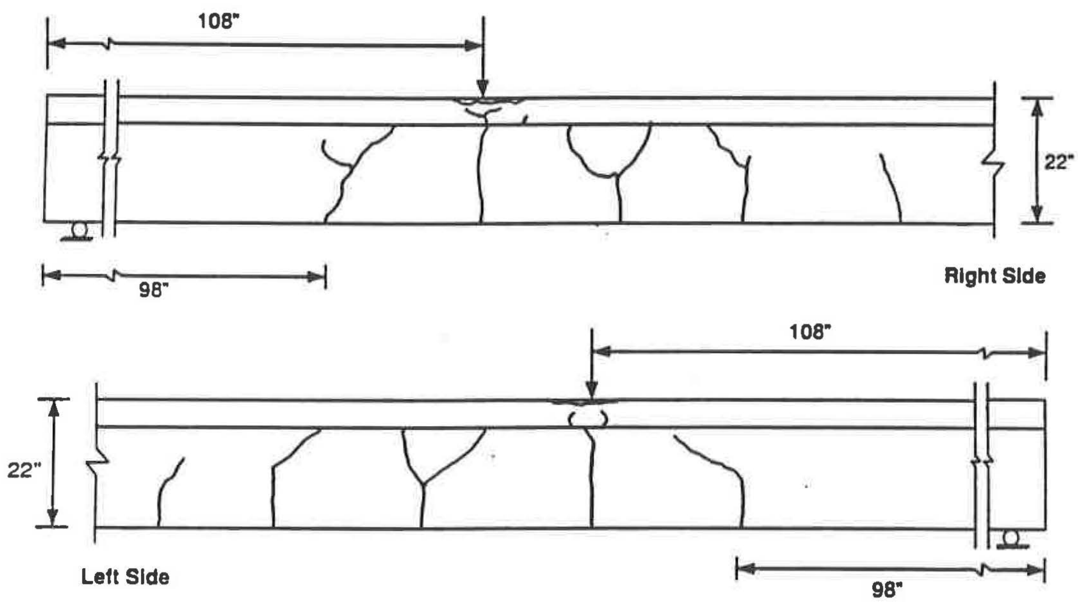


Figure D-16. Crack Diagrams for Test 16. (Beam 11, End B, 2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 108 Inch Embedment Length, Flex/Slip Failure.)

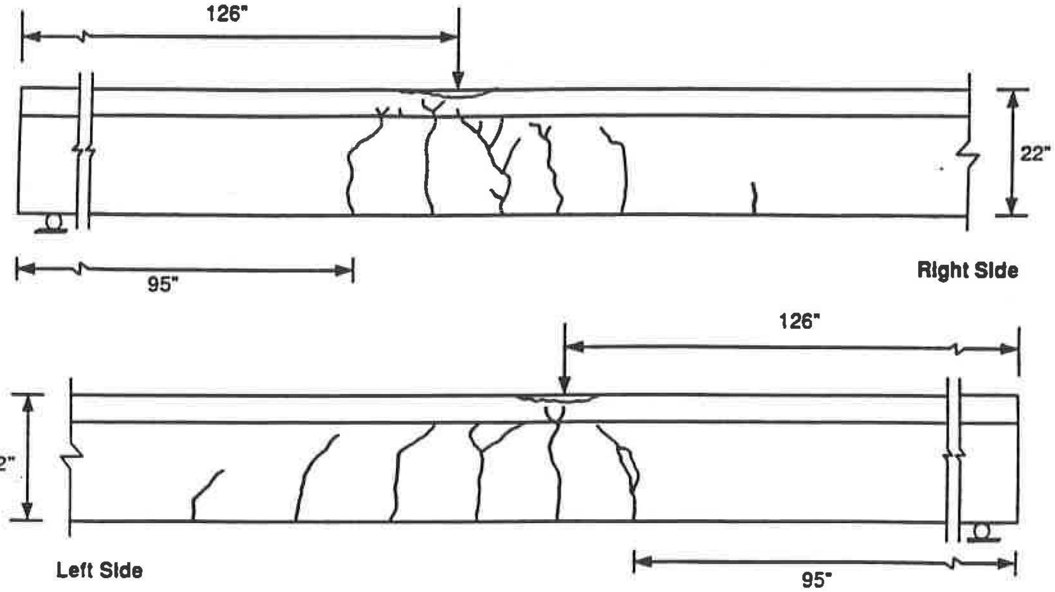


Figure D-17. Crack Diagrams for Test 17. (Beam 11, End A, 2.0 Inch Strand Spacing, Pour 4 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flexural Failure.)

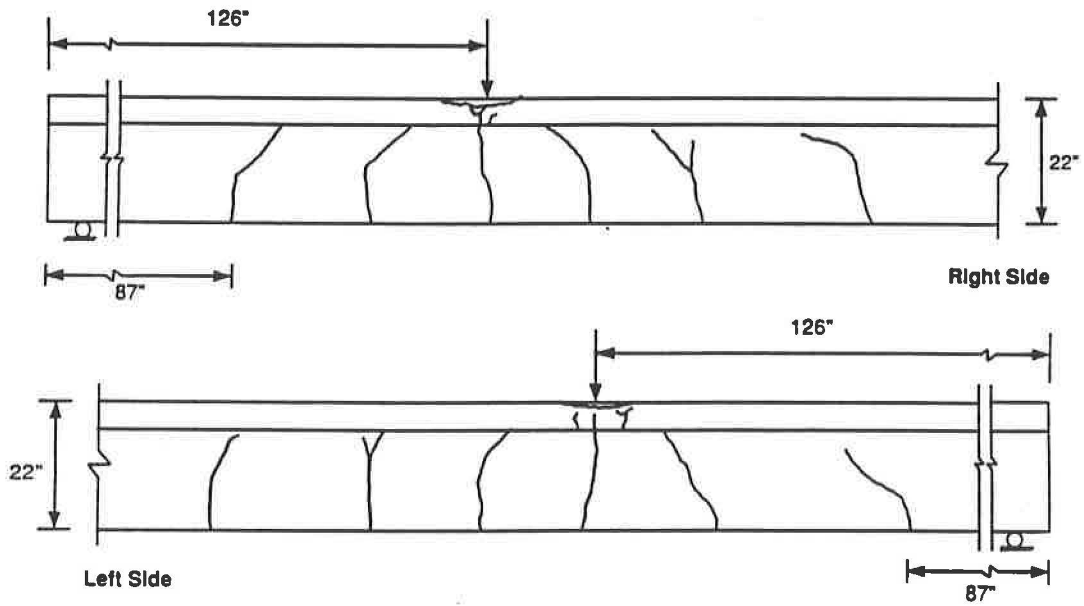


Figure D-18. Crack Diagrams for Test 18. (Beam 10, End B, 2.0 Inch Strand Spacing, Pour 3 - High Strength Mix, Unconfined, 126 Inch Embedment Length, Flexural Failure.)

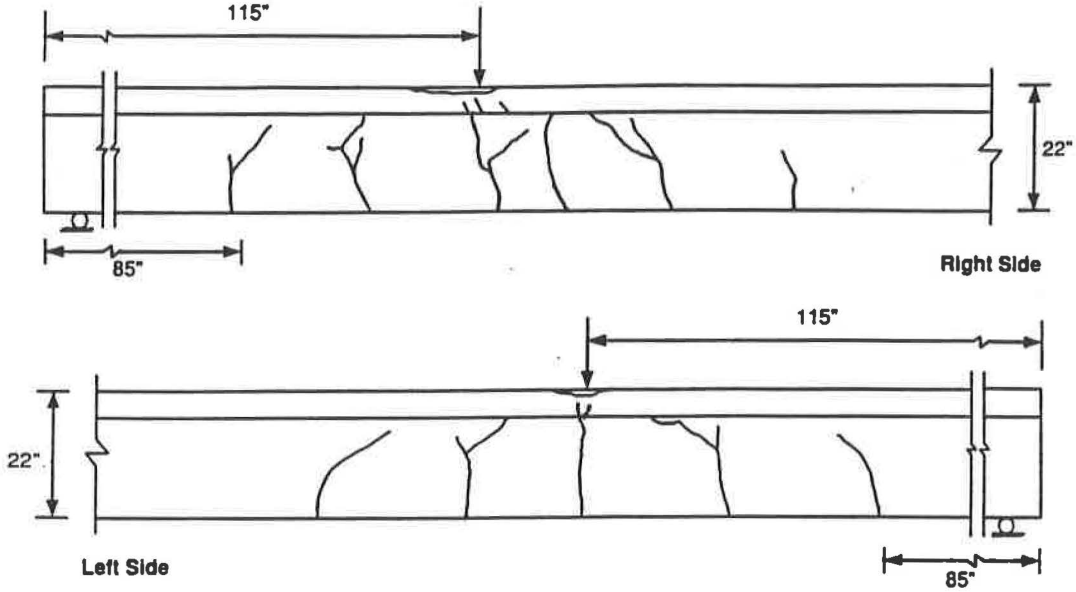


Figure D-20. Crack Diagrams for Test 20. (Beam 13, End B, 1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 114 Inch Embedment Length, Flex/Slip Failure.)

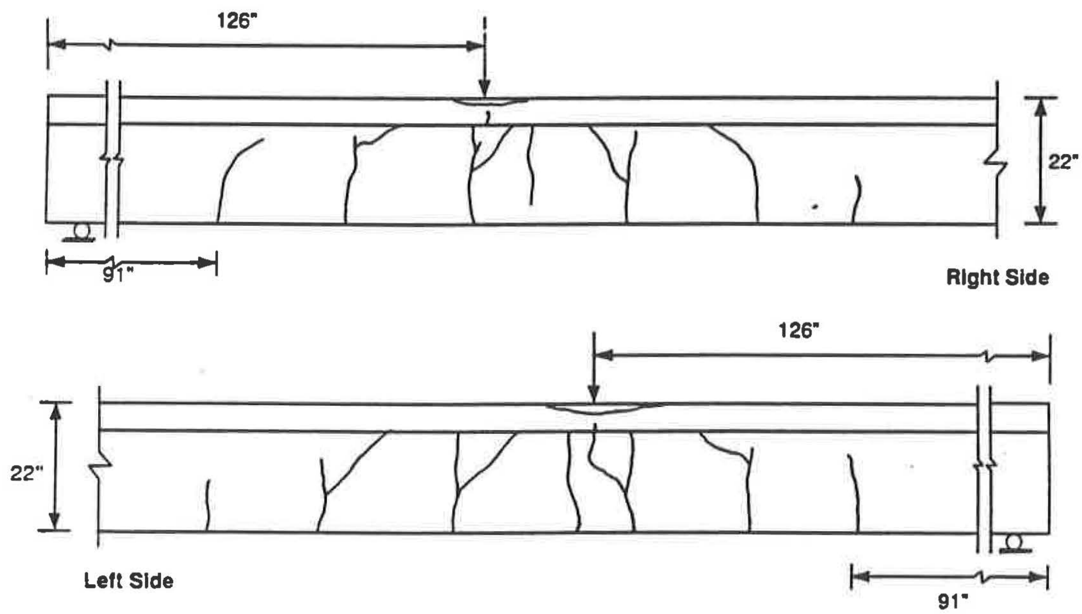


Figure D-21. Crack Diagrams for Test 21. (Beam 13, End A, 1.75 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 126 Inch Embedment Length, Flex/Slip Failure.)

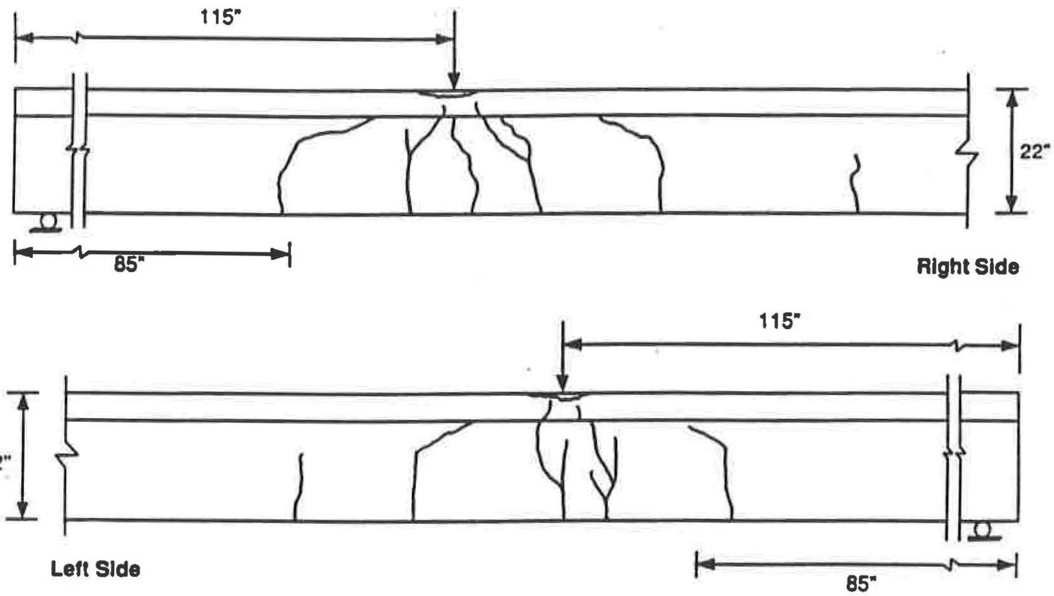


Figure D-22. Crack Diagrams for Test 22. (Beam 14, End B, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 114 Inch Embedment Length, Flex/Slip Failure.)

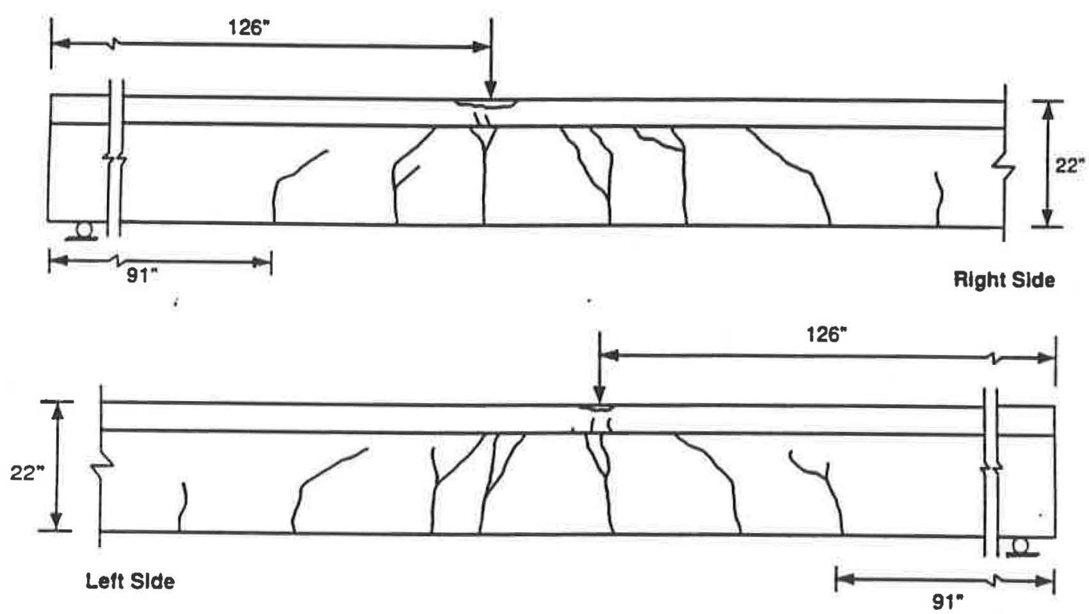


Figure D-23. Crack Diagrams for Test 23. (Beam 14, End A, 2.0 Inch Strand Spacing, Pour 6 - Normal Strength Mix, Confined, 126 Inch Embedment Length, Flex/Slip Failure.)