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16. Abstract

This report summarizes a two year research effort related to spacing and concrete cover requirements for epoxy coated prestressing strand. Today, prestressed concrete is widely used in the construction industry. Prestressed members are generally smaller than their reinforced concrete counterparts under the same loading conditions. Thus, prestressed members require less concrete and reduce the amount of steel reinforcement needed. However, the smaller amount of reinforcement in prestressed members is more vulnerable to corrosion. Protection against corrosion of prestressing steel is more critical than the non-prestressed reinforcement case since the strength of a prestressed member is a function of the prestressing tendon area. As prestressed structures become older, corrosion of the prestressing steel can become a problem.

A prestressing strand manufacturer, Florida Wire and Cable Company, has developed an epoxy coated prestressing strand. This epoxy coating has proven to be effective in preventing the corrosion of prestressing steel. The epoxy coating is impregnated with grit to improve its bonding capabilities in prestress applications. In an earlier research study the splitting at transfer in single epoxy coated strand specimens was observed. This splitting did not occur in uncoated single strand specimens with like dimensions. The splitting problem was attributed to the shorter transfer length of epoxy coated prestressing strand which causes higher bond stresses, and could be even more severe in members with multiple strands at close spacings.

This research study was undertaken to investigate the spacing and cover requirements of epoxy coated prestressing strand. By varying the parameters of strand spacing, concrete cover, and number of strands, spacing and concrete cover requirements were determined. These requirements were then compared to existing American Association of State Highway and Transportation Officials (AASHTO) specifications. Also, the transfer length of epoxy coated and uncoated prestressing strand was investigated.

17. Key Words
Prestressed Concrete, Epoxpy coated strando, cover, spacing, transfer length.

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FIGURE B-1

SPACING AND COVER OF EPOXY COATED PRESTRESSING STRANDS

FINAL REPORT

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ABSTRACT

This report summarizes a two year research effort related to spacing and concrete cover requirements for epoxy coated prestressing strand. Today, prestressed concrete is widely used in the construction industry. Prestressed members are generally smaller than their reinforced concrete counterparts under the same loading conditions. Thus, prestressed members require less concrete and reduce the amount of steel reinforcement needed. Because there is a smaller amount of reinforcement in prestressed members, protection against corrosion of prestressing steel is more critical. As prestressed structures become older, corrosion of the prestressing steel can become a problem.

A prestressing strand manufacturer, Florida Wire and Cable Company, has developed an epoxy coated prestressing strand. This epoxy coating has proven to be effective in preventing the corrosion of prestressing steel. The epoxy coating is impregnated with grit to improve its bonding capabilities in prestress applications. The grit used on the epoxy coating in this study was made from crushed glass. In an earlier research study the splitting of concrete at transfer in single epoxy coated strand specimens was observed. This splitting did not occur in uncoated single strand specimens with

like dimensions. The splitting problem was attributed to the shorter transfer length of epoxy coated prestressing strand which causes higher bond stresses, and could be even more severe in members with multiple strands at close spacings.

This research study was undertaken to investigate the spacing and cover requirements of epoxy coated prestressing strand. By varying the parameters of strand spacing, concrete cover, and number of strands, spacing and concrete cover requirements were determined. These requirements were then compared to existing American Association of State Highway and Transportation Officials (AASHTO) specifications.

IMPLEMENTATION STATEMENT

The results of this report provide the minimum cover and spacing requirements for epoxy coated prestressing strands. These requirements are based on a well designed experimental study of expoxy coated strands. The measures to be taken to use the current AASHTO minimum spacing and cover for epoxy coated prestressing strands are also presented. The error associated with using AASHTO equations for determining transfer length for epoxy coated strands is quantified.

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CHAPTER 1

Introduction

Today, prestressed concrete is widely used in the construction industry. Prestressed members are generally smaller than their reinforced concrete counterparts under the same loading conditions. Thus, prestressed members require less concrete and reduce the amount of steel reinforcement needed. Because there is a small amount of reinforcement in prestressed members, protection against corrosion of prestressing is more critical. As prestressed structures become older, corrosion of the prestressing steel can become a problem. This problem is severe in salt-water environments and structures subjected to de-icing compounds such as bridges and parking decks.

A prestressing strand manufacturer, Florida Wire and Cable Company, has developed an epoxy coated prestressing strand. This epoxy coating has proven to be effective in preventing the corrosion of prestressing steel. The epoxy coating is impregnated with grit to improve its bonding capabilities in prestress applications. In 1986 Cousins[1] experienced splitting of concrete at transfer in single epoxy coated strand specimens. This splitting did not occur in uncoated single strand specimens with like dimensions. The splitting problem was attributed to the shorter transfer length of epoxy coated prestressing strand which causes higher bond stresses, and could be even more severe in members with multiple strands at close spacings.

The purpose of this research is to investigate the spacing and cover requirements of grit impregnated epoxy coated prestressing strand. This will be accomplished though an experimental program including the fabrication and testing of pretensioned specimens with varying strand spacings and concrete covers.

CHAPTER 2

Literature Review

2.1 Theory of Transfer Length

Hoyer and Friedrich[2] showed that anchorage of prestressing wire in concrete is accomplished by the swelling of the wire at prestress transfer. This swelling is due to Poisson's effect resulting from stress reduction in the wire, and is often called the "Hoyer Effect".

While investigating the nature of bond in prestressed concrete, Janney[3], derived an equation to determine transfer length of prestressing wire. Janney, assumed friction between the wire and the concrete due to wire swelling was responsible for the majority of stress transfer. A model was developed using elastic analysis and assuming the concrete around the wire behaved as a thick walled cylinder. Using this model Janney found that tangential stresses in the concrete due to Poisson's effect would exceed the elastic range, therefore, the elastic assumption was incorrect. Janney also compared actual stress distributions in the wire with theoretical stress distributions and found the two alike with the exception of magnitude. Janney concluded that frictional bond comprised the majority of stress transfer.

While investigating transfer and development length of coated and uncoated prestressing strand Cousins, Johnston, and Zia[4] developed an analytical equation for transfer length. The equation is based on a model including an elastic and plastic zone within the transfer length, which is shown in figure 2.1.

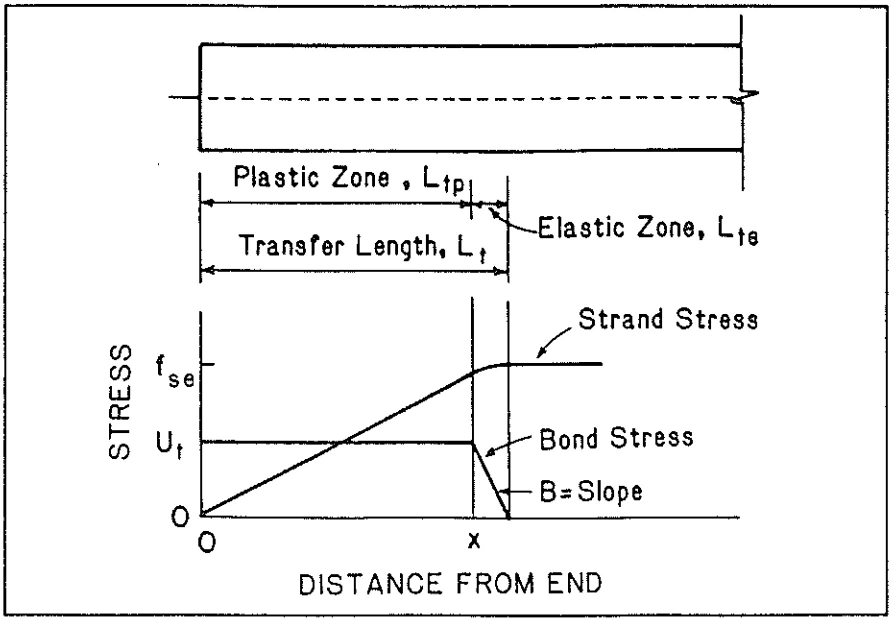


Figure 2.1 Model of Elastic and Plastic Zones Within Transfer Length

For small strand displacements relative to the concrete, bond stress was considered proportional to slip and thus termed the elastic zone. From the end of the member to the elastic zone the bond stress maintains a maximum value and this region was termed the plastic zone.

This elastic/plastic model yielded the following equation:

$$L_t = 0.5 \left(\frac{U_t \sqrt{f_{ci}}}{B} \right) + \frac{f_{se} A_s}{\pi U_t d \sqrt{f_{ci}}} \qquad (2\text{-}1)$$

Where:

U'_t & B constants based on experimental results
f_{se} = effective prestress (psi)
A_s = area of prestress (in^2)
d = nominal strand diameter (in.)
f'_{ci} = concrete strength at transfer (psi)

The authors came to the conclusion that the elastic/plastic model is an accurate depiction and the developed equation predicts transfer lengths within an acceptable degree of accuracy.

2.2 Transfer Length of Coated and Uncoated Strand

In 1963 Kaar, LaFraugh, and Mass[5] investigated the influence of concrete strength at prestress transfer on transfer length. The test program involved 1/4 inch, 3/8 inch, 1/2 inch, and 6/10 inch diameter strands in various sized members with five different concrete strengths. The strands were all stress relieved with the ultimate stress between 254,000 psi and 275,000 psi. The target stresses in the strand at transfer were 70% of the ultimate stress. Strain was measured by a Whittemore gage using brass disks embedded in the concrete at a 2 inch center to center spacing. Strain readings were made at transfer and at 1, 3, 7, 14, 28, 56, 90, 180, and 365 days after transfer. Cumulative strain was plotted versus distance along the beam. All of these cumulative curves were generally the same shape, an inclined straight line gradually changing to nearly horizontal at each end. The distance from the end of the beam to the point at which the tangents drawn to the cumulative curve deviate from the straight-line portion of the curve was defined as the transfer length. Table 2.1 shows the results for one-half inch diameter strand at transfer and concrete strengths above 4000 psi.

Concrete (psi)	Release Type & Location	Transfer Length (in.)			Number of Specimens
		1 Day	7 Day	28 Day	
4170	DE	36.0	38.0	34.0	1
	CE	37.5	36.5	35.5	
5000	DE	33.5	35.0	36.5	1
	CE	41.0	43.0	42.0	

DE=Dead End,CE=Cut End

Table 2.1 Results from Kaar, LaFraugh, and Mass[5]

Transfer lengths were adjusted to correspond to the target strand stress of 175,000 psi. Study of the data led the authors to the following conclusions:

1. Concrete strength varying from 1500-5500 psi had little influence on transfer length of seven wire strand up to and including 1/2 inch diameter.

2. Transfer lengths were increased by 20 percent to 30 percent on member ends where prestress force was released by flame cutting.

In 1963 Janney[6] studied transfer length of 250,000 psi and 270,000 psi seven-wire one-half inch diameter prestressing strand. Six specimens were cast, two with clean 270,000 psi strand, two with rusted 270,000 psi strand, and two with clean 250,000 psi strand. All specimens were 3.5 inches in height, 4.25 inches wide and eight feet in length. The 28 day compressive strength was designed to be 5000 psi with 4000 psi strength in 48 hours.

Prestress force was transferred when concrete strength reached a minimum of 4000 psi. Strain measurements were taken from mechanical gage points at two inches center to center spacing. Transfer length was taken as the distance required to achieve 100 percent of steel stress in the midspan region.

f'_u (ksi)	Surface Condition	f'_c (psi)	Transfer Length (in.)
270	Clean	4115	33
270	Rust	4090	24
250	Clean	4200	28

Table 2.2 Results from Janney[6]

Table 2.2 shows the results of this investigation, in which Janney concluded that 270,000 psi strand gives longer transfer lengths than 250,000 psi strand.

Over and Au[7] examined frictional and mechanical bond of seven-wire and single smooth wire prestressing strands. Eight specimens three inch by three inch in cross section were cast, two for each type of tendon tested, A summary of the results can be found in Table 2.3. Examination of the results led to the following conclusions:

1. Transfer length required for larger diameter strands is greater than that for smaller diameter strands.
2. Multi-wire strand requires less transfer length than single wire strands of equal strength and stress.
3. Multi-wire strands develop additional stress through mechanical bond after a general slip.

Diameter (in)	f'_c (psi)	f_{se} (ksi)	Transfer Length (in.)
1/4	4900	164	20
1/2	5500	170	35
3/8	4180	160	30
1/4 (wire)	4720	192	29

Table 2.3 Results from Over and Au[7]

While performing fatigue tests of pretensioned beams, Kaar and Hanson[8] investigated the transfer length of 3/8 inch diameter 270,000 psi strand in type III cement. Type of prestress release and strand condition were varied in the testing. The strand surface conditions were smooth, lightly rusted, and sandblasted while the prestress was transferred both gradually and suddenly. Sudden release was obtained by flame cutting. The strand stress was between 180,000 psi and 185,000 psi before release, which occurred when concrete strength reached 4,000 psi. Strains were measured along the side of the specimens immediately following transfer using a Whittemore strain gage and brass buttons at five inches center to center spacing. Transfer lengths were determined from plots of concrete strain where transfer length was defined as the length required to attain 95% of the average strain plateau. Table 2.4 shows the results of these tests. The authors found that a sudden release can increase transfer length and that the strand surface condition can effect bond.

Surface	Release	Average Transfer Length (in.)	Number of Specimens
Smooth	Gradual	23.9	39
Smooth	Sudden	29.4	37
Light Rust	Sudden	14.2	12
Sandblasted	Sudden	18.6	15

Table 2.4 Results from Kaar and Hanson[8]

Preliminary testing of epoxy coated prestressing strand was reported in a paper by Dorsten, Hunt, and Preston[9]. Seven 3.5 inch by 4.5 inch by eight feet prestressed beams were cast: three with uncoated strand and four with coated strand. The coated strand was epoxy coated with a grit concentration designed to yield bond characteristics similar to those of uncoated strand. Prestress was transferred at a strength of 4000 psi, with the strand tensioned at 75 percent of ultimate strength. All strand used was one-half inch diameter low-relaxation strand with an ultimate strength of 270,000 psi. Transfer length was measured at transfer and at 14 months. The test results are shown in Table 2.5. The use of epoxy coating increased the transfer length by 16 percent. However, at 14 months the transfer length of the coated strand was three percent less than that of uncoated. In some specimens with coated strand splitting occurred across the smallest dimension at transfer.

Strand Type	Average Transfer Length (in.)		Number of Specimens
	Initial	14 Months	
Bare	26.3 D	33.0 D	4
	27.5 C	33.5 C	4
Coated	33.3 D	35.0 D	3
	29.3 C	29.7 C	3

D=Dead End, C=Cut End

Table 2.5 Results from Dorsten, Hunt, and Preston[9]

Cousins, Johnson, and Zia[4] studied the transfer length of epoxy coated prestressing strand as compared to uncoated strand. All prestressing steel was seven wire low relaxation strand with an ultimate strength of 270,000 psi. Fifty-three specimens of varying dimensions were cast using uncoated and coated strand of three different sizes: three-eighths, one-half, and six-tenths inch. Varying grit densities in the epoxy coated strand were investigated including the medium-grit density which is the standard production line. The grit used on the epoxy coated strands in this study was made from crushed glass. Prestress of 64 percent to 68 percent of ultimate strand strength was transferred when concrete compressive strength reached 4000 psi. Strain measurements were made at one, seven, 28, 90, 180, and 365 days using a Whittemore type extensometer and Whittemore gage points.

Diameter (in.)	Coating	T.L. (in.)	Number of Samples
3/8	UN	34	16
3/8	CM	14	12
1/2	UN	50	20
1/2	CL	28	8
1/2	CM	19	16
1/2	CH	17	8
0.6	UN	56	10
0.6	CM	30	12

UN=Uncoated, CL=Coated Light, CM=Coated Medium,
CH=Coated Heavy, T.L.=Transfer Length

Table 2.6 Results from Cousins, Johnson, and Zia[4]

A summary of the results is found in Table 2.6. Transfer length was determined as the distance to transfer 100% of the prestressing force. The authors also made the following conclusions:

1. Transfer length of grit-impregnated epoxy coated prestressing strand is shorter than transfer length of like diameter uncoated strand.
2. Transfer length increases as grit density of epoxy

coated strand decreases.

3. Splitting occurred in some epoxy coated specimens at release probably due to high bond stresses. Thus, splitting may be a problem with thin cover, close strand spacing, or poor confinement.
4. Transfer lengths of coated strand increase more than uncoated strand over time, however, not enough to exceed the longer transfer lengths of uncoated strand.

Deathrage and Burdette[10] studied the transfer length of one-half inch and six-tenths inch low relaxation 270,000 psi strand in an investigation of development length and lateral spacing requirements for prestressed beams. In addition to other castings, six transfer specimens were cast each 12 feet long with a single uncoated strand located centrally in the cross section. Strain measurements were made using a Mayes Mechanical Strain Indicator and mechanical gage points. Strain versus distance along the prism was plotted, and the transfer length determined by the Slope-Intercept method. The Slope-Intercept method consists of drawing a horizontal line representing the strain plateau and a straight line representing the slope of the increasing strain. The distance to the intersection of these two lines from the beam end is defined as the transfer length. The strand transfer was obtained by flame cutting at one end which was designated as the cut end. The opposite end was designated the dead end.

Table 2.7 provides a summary of the data obtained from the transfer prisms. Two 3.5 inch by 3.5 inch prisms cracked at the ends upon prestress transfer.

Strand Diameter (in.)	Average f_{sc} (ksi)	Average T.L. (in.)	Number of Specimens
1/2	160	26.62*	2
1/2	185	30.87	2
0.6	185	30.88	2

f'_{ci}=4760 psi, * Ends Cracked, T.L.= Transfer Length

Table 2.7 Results from Deathrage and Burdette[10]

Table 2.8 shows a summary of the I-Beam transfer data which indicates the conclusions that weathering has a significant measurable effect of decreasing transfer length. The authors also concluded that increasing strand diameter increases transfer bond, and the "Slope-Intercept" method of obtaining transfer length results compares favorably to the

Diameter (in.)	Condition	Average T.L. (in.)	Number of Specimens
1/2	Milled	32.50	4
1/2	W-1 Day	23.25	4
1/2	W-3 Day	19.50	8
1/2 s	Milled	32.50	4
1/2 s	W-3 Day	31.00	4
9/16	Milled	34.50	4
9/16	W 3-Day	27.50	4
6/10	Milled	24.38	8

T.L.=Transfer Length, W=Weathered

Table 2.8 I Beam Data of Deathrage and Burdette portion of the American Association of State Highway Transportation Officials (AASHTO)[11] code equation for development length which predicts transfer length.

Unay, Russell, Burns, and Kreger[12] studied transfer length of one-half inch and six-tenths inch diameter uncoated prestressing strand. Sixty two transfer length specimens were tested with variables including number of strands, strand spacing, and strand diameter. Transfer length data was acquired from surface concrete strains, prestressing steel strains, and end slip measurements. Concrete strain measurements were the main source for transfer length information. Mechanical gage points were attached to each side of each specimen at the centroid after casting. A mechanical strain gage was used to measure relative distances between the points. Absolute strain readings were represented by four independent sets of raw data which were then "smoothed" by a computer software program and plotted versus the length of the beam. Two separate transfer lengths were determined, one distance at which 95 percent and one distance at which 100 percent of the prestressing stress was transferred. Table 2.9 gives a summary of the information obtained.

Strand Size	Transfer Length at 95% of Transfer (in.)	Number of Beam Ends
0.5"	30.1	32
0.6"	39.4	43

Table 2.9 Results from Unay, Russell, Burns, and Kreger[12]

The authors discovered that single strand specimens released at full tension do not provide reliable transfer length data, larger cross sections produce smaller transfer lengths, good consolidation reduces transfer length, bond characteristics are affected by strand diameter, and transfer lengths did not change with an increase in strand spacing from 2.0 inches to 2.5 inches. Transfer lengths for beam ends adjacent to flame cutting were significantly longer than transfer lengths of beam ends not adjacent to flame cutting. Single strand specimens yielded strain plots that were highly erratic and made transfer length determination difficult. In addition, the authors concluded that transfer lengths of both one-half inch and six-tenths inch diameter strand are closely predicted by the portion of the AASHTO[11] equation for development length which predicts transfer length.

To date there has been extensive study of the transfer length of uncoated prestressing strand. However, research is limited as to the transfer length of epoxy coated prestressing stand. Although the standard production grit intensity of epoxy coated strand had been designed to yield a bond mechanism similar to that of uncoated strand, there is some concern that this is not so. Previous research indicates that epoxy coated strand may develop a shorter transfer length than uncoated strand and that current AASHTO strand spacing and concrete cover requirements for prestressing steel may not be sufficient to transfer the prestressing force when epoxy coated strand is used. A comprehensive study of spacing and cover requirements of epoxy coated strand in prestressing members is necessary.

Previous research shows a high degree of scatter for transfer length measurements. As reported earlier, the transfer length of one-half inch diameter strand has been measured as anything from 24 to 50 inches. Several factors may effect this variability: 1.) different definition of transfer length (from transferring 100 percent to 95 percent of strand stress to the "Slope-Intercept" method), 2.) variations in material properties of strand and concrete, 3.) variations in surface condition of strand, 4.) different release methods (sudden versus gradual), and 5.) variations in the number of strands and confinement reinforcement in a section. None of these variables are accounted for in the portion of the AASHTO equation for development length which predicts transfer length, and therefore, this equation is sometimes not representative of the transfer length within a beam. Thus, further investigation of the transfer length of uncoated strand is warranted.

CHAPTER 3

Objective and Scope

The objectives of the research are to investigate the spacing and cover requirements for epoxy coated prestressing strand. Specifically, these objectives are:

1) To determine experimentally the spacing and cover requirements at transfer of prestressing force of epoxy coated prestressing strand as compared to the requirements for bare strand.
2) To compare these results to design requirements set forth by AASHTO[11] for spacing, cover, and transfer length.
3) To make recommendations for design code changes if warranted.

These objectives were accomplished through an experimental testing program including fabrication and testing of forty pretensioned, prestressed beam specimens of varying clear cover and strand spacing.

CHAPTER 4

Test Methodology

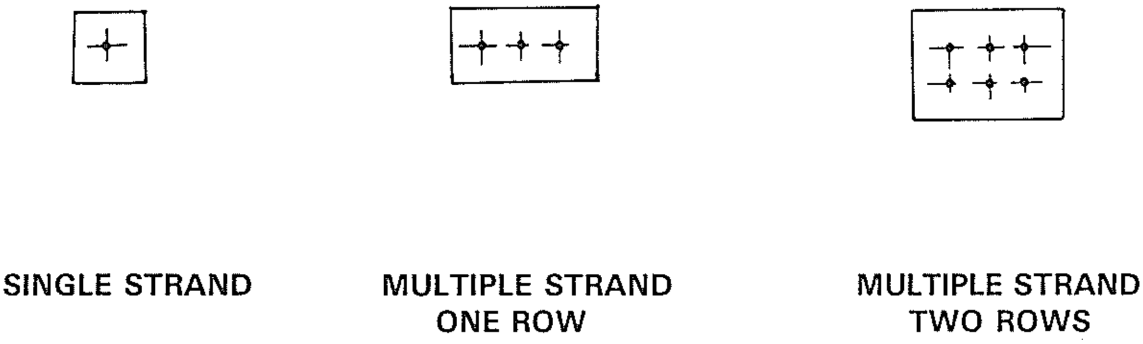
4.1 Program Introduction

To complete this research, forty specimens were fabricated and tested in the Auburn University Structural Engineering Research Laboratory. These specimens were designed to investigate the parameters of strand spacing, strand configuration, and concrete cover and the effect of these parameters on transfer length.

These parameters were varied in a method to determine as closely as possible, the minimum concrete cover and strand spacings required for epoxy coated prestressing strand. As a result of this experimentation a large body of information about transfer length of epoxy coated and uncoated prestressing strand was generated.

4.2 Specimen Description

Three types of pretensioned prestressed specimens were fabricated: 1.) single strand, 2.) multiple strands placed in one layer (three strands), and 3.) multiple strands placed in two layers (six strands). All strands used in this study were 0.5 inches in diameter. Figure 4.1 shows the cross sections of the three types of specimens. Specimens contained no confinement reinforcement. Beam lengths for the first pour were 11 feet for uncoated specimens and 9 feet for coated specimens. To insure that the full transfer length was achieved within a specimen, beam lengths were adjusted after the first casting to the following: specimens with coated strand, 10 feet, and specimens with uncoated strand, 12 feet.


SINGLE STRAND

MULTIPLE STRAND ONE ROW

MULTIPLE STRAND TWO ROWS

Figure 4.1 Cross Sections of Three Types of Specimens Fabricated

Specimens were designated using a combination of letters and numbers. From the designation, the spacing, cover, and strand arrangement can be determined for a specific specimen. Each beam had a designation consisting of five parts as follows:

1) The number three or six to determine the number of strands and strand pattern. The absence of a number corresponds to a single strand specimen.

2) The letter C or U to indicate coated strand and uncoated strand, respectively.
3) A number designating the smallest clear cover in the specimen. Clear cover is measured in inches with the decimal always following the first number (ie. 225 is 2.25 inches).
4) Two letters indicating each end of the beam.
5) A number designating the center to center spacing of strands in a specimen (both horizontal and vertical where applicable). The spacing is measured in inches with the decimal following the first number (i.e. 35 is 3.5 inches). The absence of a number indicates a single strand specimen.
6. If an asterisk appears at the end of the beam designation this denotes a beam with duplicate designation.

As an example, 3C225AB3 is a three strand specimen made with coated strand and with 2.25 inches clear cover and three inches spacing with ends designated A and B. Dimensions of all the specimens can be found in the Tables 4.1, 4.2, 4.3 and 4.4. Concrete stresses immediately after transfer are discussed in section 4.5.

Beam sides were designated by always looking down the beam from the end of the beam with highest alphabetical letter designation. For example, in a beam with letter end designations C and D the left side corresponds to the left when looking from C to D. Likewise the right side corresponds to the right when looking from C to D.

Individual strand designation was accomplished in a similar manner. Always looking down the beam from the highest alphabetical letter designation the strand position designation is defined by Figure 4.2. Therefore, an individual strand had the same designation throughout a specimen.

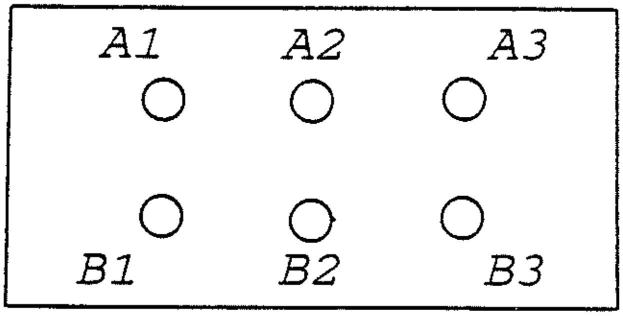


Figure 4.2 Strand Designation Looking at Beam End With Highest Alphabetical Letter

Beam ID	Pour #	Size	Clear Cover (in.)
U15AB0	1	3.5" X 3.5"	1.5
U15CD0	1	3.5" X 3.5"	1.5
C15EF0	1	3.5" X 3.5"	1.5
C15GH0	1	3.5" X 3.5"	1.5
U175AB0	2	4" X 4"	1.75
C175CD0	2	4" x 4"	1.75
C175EF0	2	4" X 4"	1.75
U1625AB0	3	3.75" X 3.75"	1.625
C1625CD0	3	3.75" x 3.75"	1.625
C1625EF0	3	3.75" X 3.75"	1.625

Table 4.1 Single Strand Beam Dimensions

Beam ID	Pour #	Size	Spacing (in.)	Clear Cover (in.)	
				Side	Top/Bottom
6U225AB3	6	8" X 11"	3.0	2.25	2.25
6C225CD3	6	8" X 11"	3.0	2.25	2.25
6C225EF3	6	8" X 11"	3.0	2.25	2.25
6C20AB275	7	7.25" X 10"	2.75	2.0	2.0
6C225CD275	7	7.75" X 10.5"	2.75	2.25	2.25
6C225EF275	7	7.75" X 10.5"	2.75	2.25	2.25
6U20AB25	7	7" X 9.5"	2.5	2.0	2.0
6C20CD25	7	7" X 9.5"	2.5	2.0	2.0
6C225EF25	7	7.5" X 10"	2.5	2.25	2.25

Table 4.2 Dimensions of Specimens with Multiple Strands in Two Layers

Beam ID	Pour #	Size	Spacing (in.)	Clear Cover (in.)	
				Side	Top/Bottom
3U175AB2	2	4" X 8"	2.0	1.75	1.75
3C175CD2	2	4" X 8"	2.0	1.75	1.75
3C175EF2	2	4" X 8"	2.0	1.75	1.75
3U175AB225	3	4" X 8.5"	2.25	1.75	1.75
3C175CD225	3	4" X 8.5"	2.25	1.75	1.75
3C175EF225	3	4" X 8.5"	2.25	1.75	1.75
3U175AB25	4	4.5" X 9"	2.5	1.75	2.0
3C175CD25	4	4.5" X 9"	2.5	1.75	2.0
3C175EF25	4	4.5" X 9"	2.5	1.75	2.0
3U175AB225*	4	4" X 9"	2.25	2.0	1.75
3C175CD225*	4	4" X 9"	2.25	2.0	1.75

Table 4.3 Beam Dimensions for Specimens 3U175AB2, 3C175CD2, 3C175EF2, 3U175AB225, 3C175CD225, 3C175EF225, 3U175AB25, 3C175CD25, 3C175EF25, 3U175AB225*, and 3C175CD225*

Beam ID	Pour #	Size	Spacing (in.)	Clear Cover (in.) Side	Clear Cover (in.) Top/Bottom
3C175EF225*	4	4" X 9"	2.25	2.0	1.75
3C225AB275	5	5" X 10.5"	2.75	2.25	2.25
3C20CD275	5	4.5" X 10"	2.75	2.0	2.0
3C20EF275	5	4.5" X 10"	2.75	2.0	2.0
3U20AB25	5	4.5" X 9.5"	2.5	2.0	2.0
3C20CD25	5	4.5" X 9.5"	2.5	2.0	2.0
3C20EF25	5	4.5" X 9.5"	2.5	2.0	2.0
3C225AB3	6	5" X 11"	3.0	2.25	2.25
3C225CD3	6	5" X 11"	3.0	2.25	2.25
3C20EF3	6	4.5" X 10.5"	3.0	2.0	2.0

Table 4.4 Beam Dimensions for Specimens 3C175EF225*, 3C225AB275, 3C20CD275, 3C20EF275, 3U20AB25, 3C20CD25, 3C20EF25, 3C225AB3, 3C225CD3, and 3C20EF3

4.3 Materials

4.3.1 Concrete

The concrete mix was designed to yield a compressive strength of 4,500 psi in four to five days and a minimum compressive strength of 5,500 psi in 28 days so that conditions in an actual prestressing plant could be imitated. The concrete was delivered by a local ready mix concrete supplier and super-plasticizer was added to obtain a minimum slump of six inches at casting. After the first three pours the mix was not performing as designed. The mix was redesigned by primarily adding more cement and better results were obtained. However, the redesigned mix did not meet the original specifications of concrete strength gain. Tables 4.5 and 4.6 show the two mix designs and the pours they were used in. It was believed the difference in the mixes would not effect bond since concrete strengths in this range appear to have a negligible effect on transfer length.[5]

Cement	705	lbs.
Water	30.5	gal.
Sand (River)	1160	lbs.
Stone #57	1925	lbs.
Master Bldrs 122HE (Water Reduction)	21.2	oz.
Master Bldrs Rheobuild 1000 (Super Plasticizer)	56.4	oz.
Master Bldrs MBVR (Sufficient to entrain 2% to 4% total air)		

Table 4.5 Mix Design for Pours One, Two, and Three

Cement	752	lbs.
Water	31	gal.
Sand (natural)	1108	lbs.
Stone #57	1925	lbs.
Master Bldrs 122HE (Water Reduction)	120	oz.
Master Bldrs Rheobuild 1000 (Super Plasticizer)	60	oz.
Master Bldrs MBVR....	(Sufficient to entrain 0-3% total air)	

Table 4.6 Mix Design For Pours Four, Five, Six, and Seven

Nine six inch by 12 inch concrete cylinders were made with each casting so that the concrete strength could be monitored up to transfer and at 28 days of concrete age. The specimens and cylinders were moist-cured in the same location and environment as the specimens. To insure moist curing, specimens were kept wet and covered with plastic. Table 4.7 shows the concrete compressive strengths for the different pours.

Pour #	Days to Transfer	f'_{ci} (Transfer)	f'_c (28 days)
1	7	4,224	5,270
2	6	4,450	5,452
3	10	4,244	4,639
4	6	5,157	5,747
5	6	4,686	6,163*
6	7	4,718	5,806
7	6	4,730	6,189

* 35 days

Table 4.7 Concrete Compressive Strengths

4.3.2 Prestressing Steel

All prestressing steel was manufactured under ASTM A-416-90A[13] by Florida Wire and Cable Company (FW&C). The strands used were both uncoated and epoxy coated seven wire 270,000 psi guaranteed ultimate tensile strength, low-relaxation strand. Only one-half inch diameter strand was used in this study and Figure 4.3 shows the coated and uncoated strand.

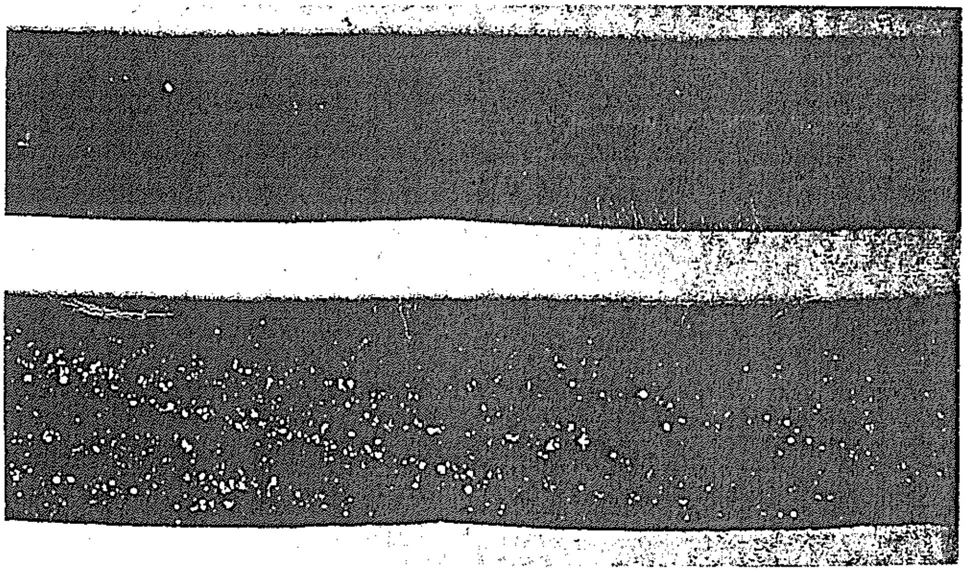


Figure 4.3 Coated and Uncoated Strand

The uncoated strand was used in control to insure satisfactory testing. The uncoated strand was from one production lot, however, the coated strand was from two production lots. The coated strand used is marketed under the name Flo-Bond by FW&C, and is a normal one-half inch diameter strand with an epoxy coating. The epoxy coating is imbedded with crushed glass to improve bonding with concrete. The actual coating thickness was not measured. Some coated strand sections had noticeably less grit than others, as shown in Figure 4.4. However, these "gritless" sections were either placed in the middle of beams to minimize interference with transfer length determination, or not used.

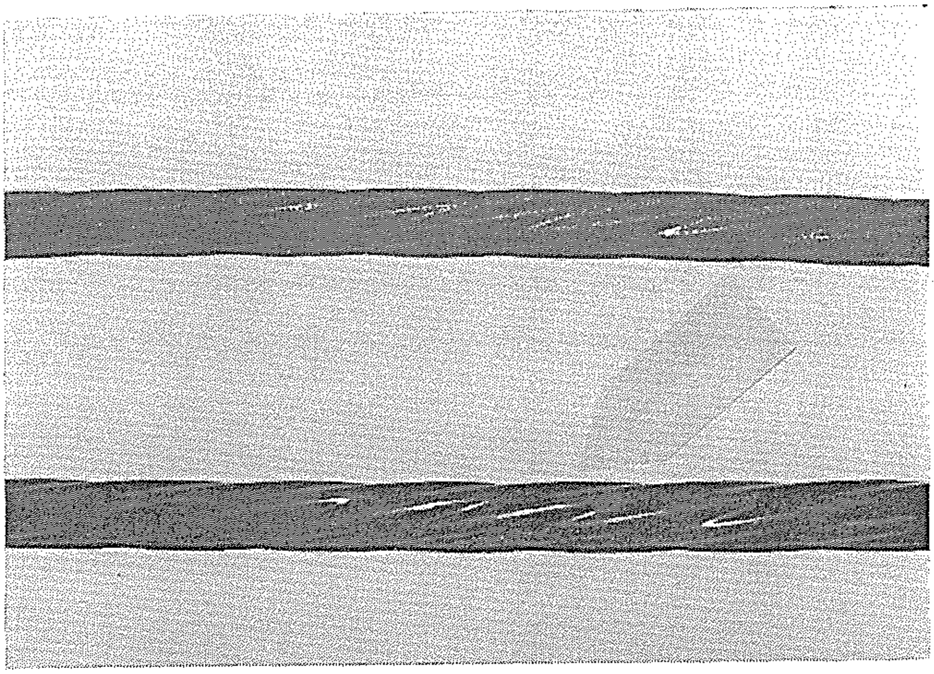


Figure 4.4 Two Coated Strand Sections with Arrow Pointing to "Gritless" Section

Florida Wire and Cable conducted load tests from each lot of strand. Average Modulus of Elasticity was determined as 28,600 ksi the yield strength as 264.36 ksi and Ultimate Strength as 284.35 ksi. The test results can be found in Appendix A.

4.4 Specimen Fabrication

Two forty-six foot stressing beds were constructed in the Auburn University Structural Engineering Research

Laboratory to complete this work so that two lines of specimens could be fabricated during one pour. Figure 4.5 shows the stressing beds. Two reinforced concrete end blocks were secured a clear distance of forty-six feet apart to a two foot thick structural floor by post-tensioning the blocks to the floor with Dywidag Threadbars, thus forming one stressing bed. The strand was pulled through an eight inch diameter hole in the blocks and held in place at the ends by chucks and steel plates. Splice chucks were used to splice coated and uncoated strand together in one line so that coated and uncoated strand specimens with equal strand

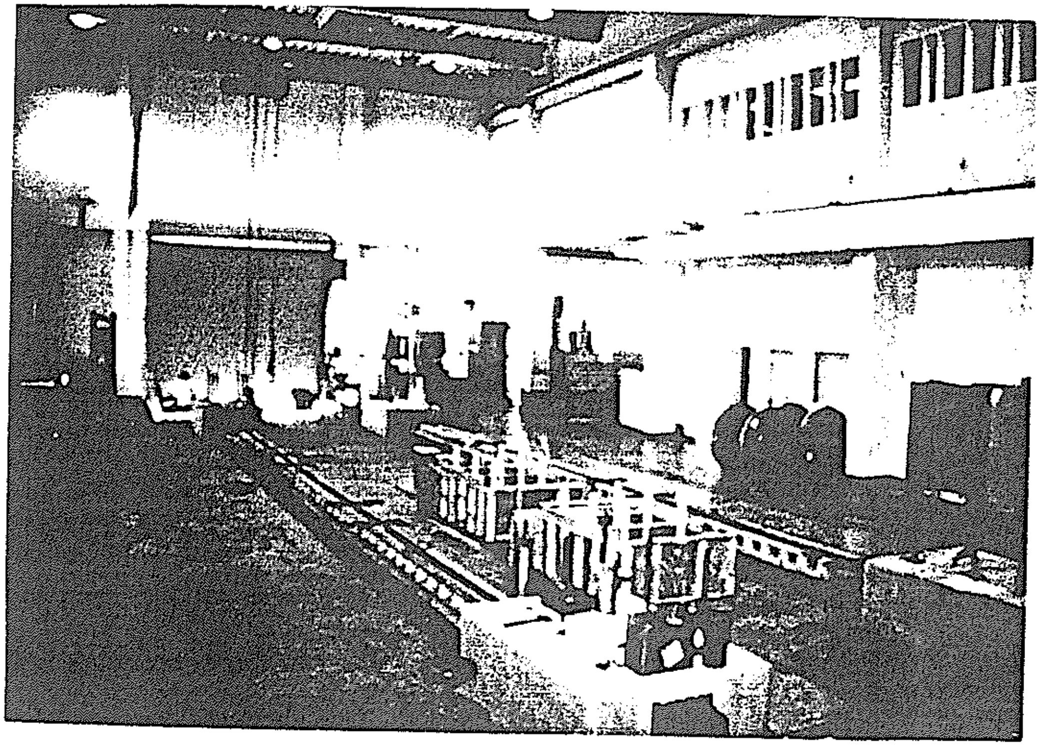


Figure 4.5 Stressing Beds

stresses prior to release could be fabricated.

Formwork was fabricated so that the strands could be stressed before placing the formwork and the beam dimensions could be changed with minimal adjustments. Formwork consisted of 8 foot long by 7.5 inches high sections with holes drilled on a 2 inch center to center to spacing. The holes were located at an elevation corresponding to the center of gravity of the specimens and the prestressing force. Threaded inserts were placed in these holes as in Figure 4.6. The threaded insert system provided a means of placing gage points into the concrete during curing.

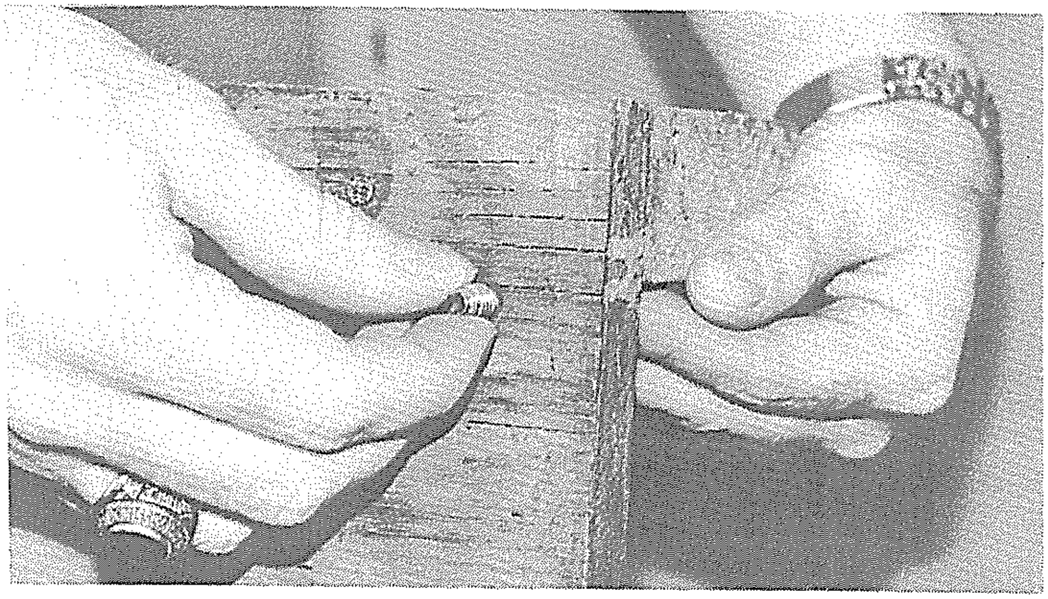


Figure 4.6 Placing Threaded Inserts Into Formwork

Each 8 foot by 7.5 inch section formed a side of a beam. Sections were set end to end in the stressing bed to form a line of beams. To divide the line into separate specimens, wooden bulkheads were used as dividers. The sections were bolted to plywood bottoms, which were located on moveable supports. The moveable supports allowed vertical adjustment of the entire form to fine tune alignment of the strand with gage points. An overhead view of a typical set up is shown in Figure 4.7. When new beam dimensions were desired, bottom inserts and top strips were fabricated, which facilitated beam adjustment without redrilling of gage point holes.

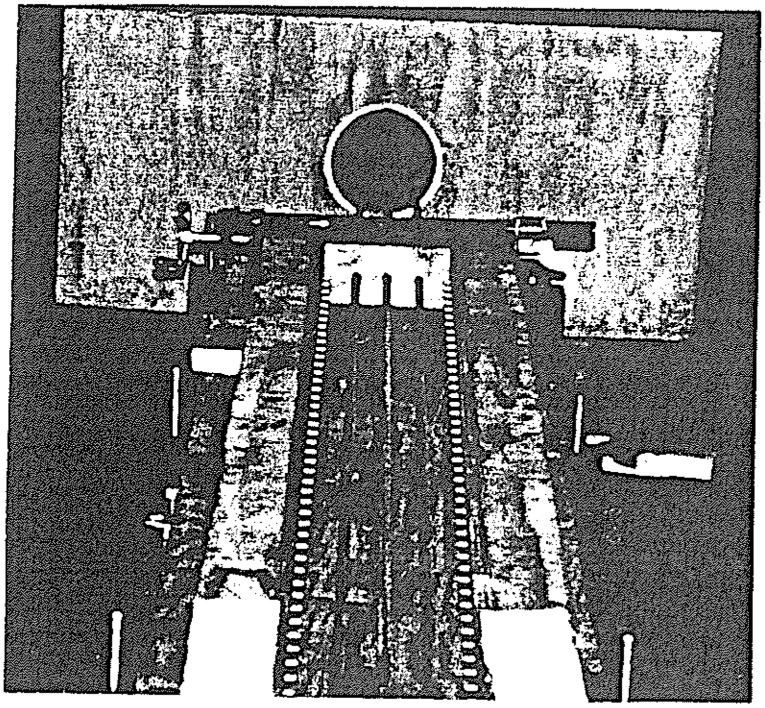


Figure 4.7 Overhead View of Typical Setup

Gage points were secured before concrete was poured. After the concrete sufficiently hardened, the screws were taken out which left a threaded insert imbedded in the concrete to act as a gage point. When the forms were removed the gage point was left in the concrete, flush with the surface of the beam, and appeared as shown in Figure 4.8. Sometimes grout leaked into the insert and this was removed using a wire brush. Occasionally gage points were damaged during a pour or during form removal. In this case the point was numbered but no data taken from it.

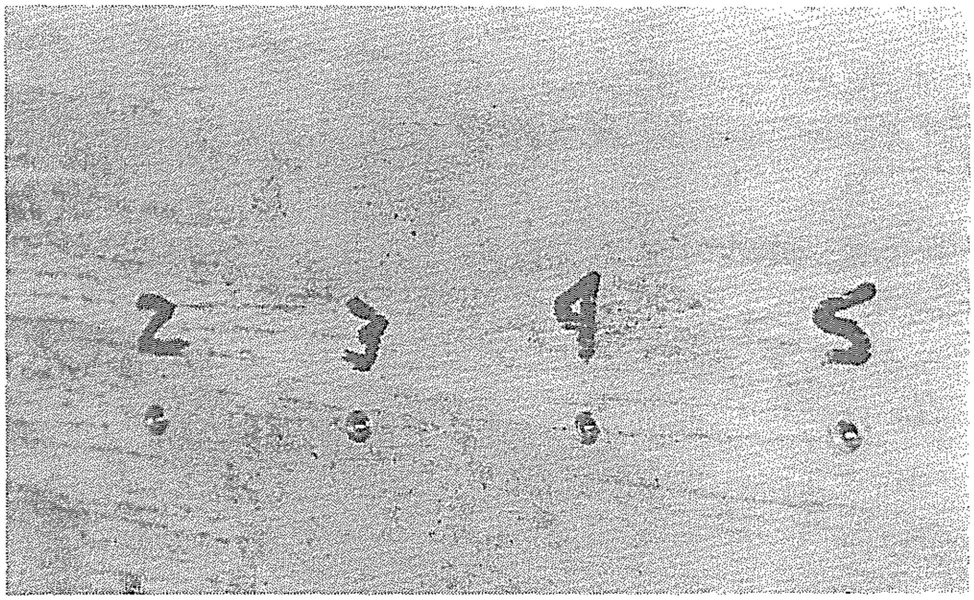


Figure 4.8 Gage Point Embedded in Specimen

4.5 Stressing

Stressing was accomplished using a hydraulic jack and hand pump. Force in the strand was monitored using a load cell at the dead end chuck. A pressure gauge attached to the jack was used to roughly check strand stress and to see that the dead end load cell was operating properly. Figures 4.9, and 4.10, show the live end and dead end, respectively.

The stressing operation proceeded in the following manner:

1) The strand was pulled to slightly above the stress desired immediately before transfer.
2) Chuck wedges on the live end were set in place.
3) The force in the hydraulic jack was released, transferring the load to the live end chuck.
4) Final formwork adjustment was made.
5) Strand was restressed and shims placed under the live end chuck to adjust for chuck slip losses and so that the desired stress immediately before transfer was achieved.

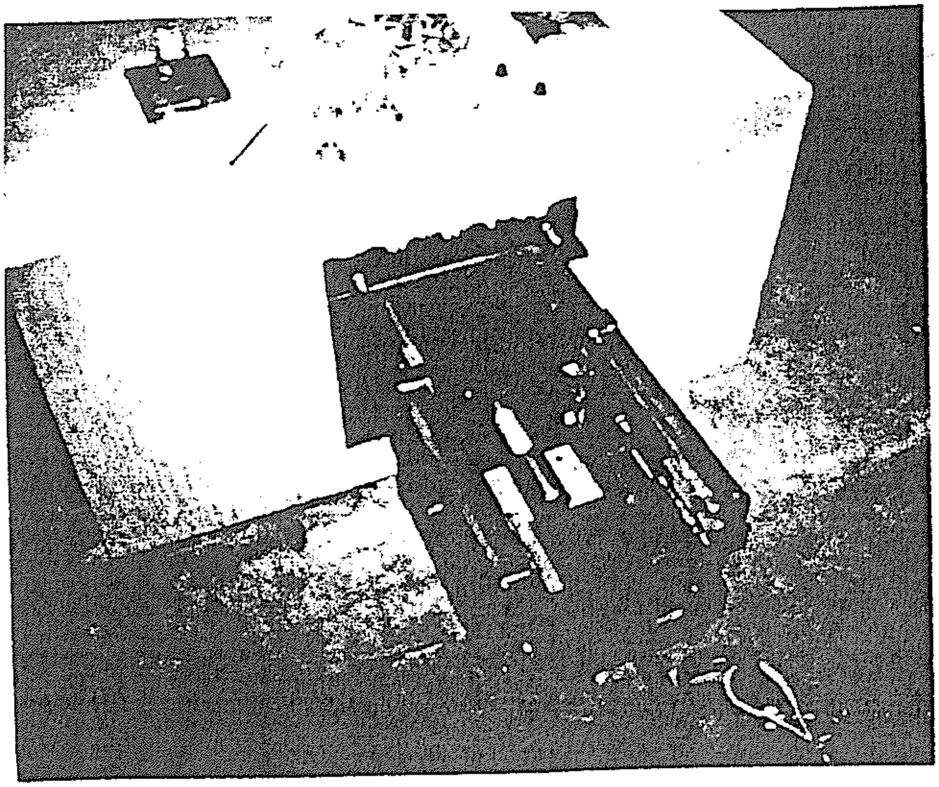


Figure 4.9 Live End

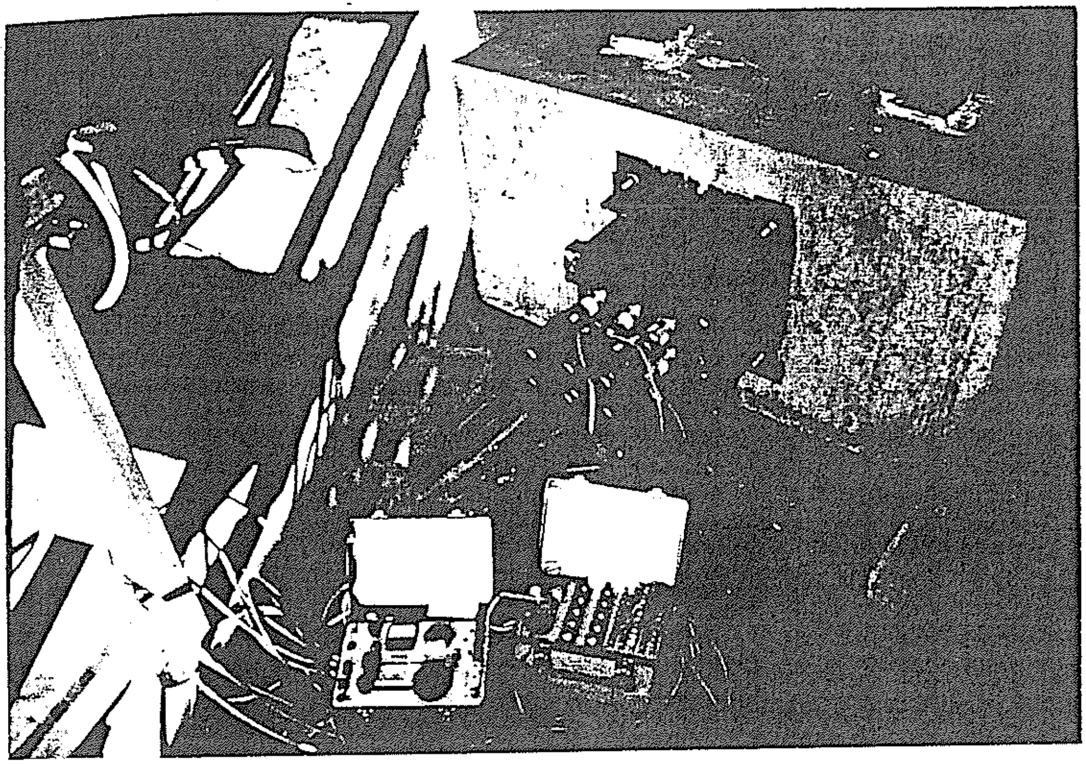


Figure 4.10 Dead End

6) Stress in the strand was recorded until transfer using the dead load cells.

Chuck slip and loss due to slip was not officially recorded, however, it was noted that the epoxy coated strand slipped more than the uncoated strand. Jacking stresses never exceeded 85 percent of the specified yield strength of the prestressing strand, (f_{py}). Tables 4.8, 4.9, and 4.10 show the stresses recorded for each strand of each specimen immediately before pouring. The strand stress immediately before pouring averaged 74.4 percent, 76.3 percent, and 77.0

percent of 270 ksi for the single, three, and six strand beams, respectively. This yielded an average strand stress of 67.6 percent, 69.9 percent, and 70.7 percent of 270 ksi for the single, three, and six strand specimens, respectively, immediately after transfer.

Beam ID	Strand Stress (ksi)
U15AB0	204.40
U15CD0	
C15EF0	
C15GH0	
U175AB0	198.95
C175CD0	
C175EF0	
U1625AB0	199.10
C1625CD0	
C1625EF0	

Table 4.8 Strand Stresses Immediately Before Pouring for Specimens with a Single Strand

The strand stress immediately after transfer is the average strand stress immediately before pouring minus the estimated prestress losses due to elastic shortening. The estimated losses is the Modulus of Elasticity of the prestressing steel multiplied by the average concrete strain immediately following transfer. The average concrete strain is the magnitude of the strain plateau in the concrete strain plot immediately after transfer for the specimen in which the strand was located. The calculated average strand stresses used for the immediately after transfer percentages are found in Appendix E.

Stress in the concrete was always checked and considered in the dimensioning of the beam. Concrete stresses, due to prestressing force, never exceeded the limitations set by the AASHTO code.[11] The average concrete compressive stresses were 2.21 ksi, 2.38 ksi, and 2.46 ksi for single, three, and six strand specimens, respectively.

Beam ID	Strand Stress at Position (ksi)						Avg. (ksi)
	A1	A2	A3	B1	B2	B3	
6U225AB3 6C225CD3 6C225EF3	203.7	203.5	202.6	205.8	207.8	210.6	205.7
6C20AB275 6C225CD275 6C225EF275	210.9	206.3	209.7	206.5	204.2	205.6	207.2
6U20AB25 6C20CD25 6C225EF25	211.5	211.5	207.7	209.8	212.4	212.2	210.9

Table 4.9 Average Strand Stresses Immediately Before Pouring for Multiple Strand Specimens in Two Layers

Beam ID	Strand Stress at Position (ksi)			Average (ksi)
	B1	B2	B3	
3U175AB2 3C175CD2 3C175EF2	195.7	198.3	195.4	196.5
3U175AB225 3C175CD225 3C175EF225	198.0	197.4	197.4	197.6
3U175AB25 3C175CD25 3C175EF25	207.5	208.3	209.6	208.5
3U175AB225* 3C175CD225* 3C175EF225*	210.3	207.5	209.0	208.9
3C225AB275 3C20CD275 3C20EF275	209.0	211.2	211.8	210.7
3U20AB25 3C20CD25 3C20EF25	206.7	215.6	210.7	211.0
3C225AB3 3C225CD3 3C20EF3	208.5	207.1	208.8	208.1

Table 4.10 Average Strand Stresses Immediately Before Pouring for Specimens with Multiple Strands in One Layer

4.6 Casting

The concrete arrived by truck, and after checking the slump the concrete was placed using a one-half cubic yard capacity bucket. After the concrete was placed in the forms and thoroughly vibrated with an electric vibrator, the specimens were lightly trowled and covered with plastic. The beams were kept wet until release to insure moist curing and to reduce shrinkage losses. The concrete cylinders were rodded, lightly finished and kept near the specimens during curing to insure accurate concrete strength representation.

4.7 Prestress Release

All specimens were released suddenly by acetylene torch to mimic procedures in a prestressing plant. During the first pour, spalling of two uncoated strand specimens occurred due to prestress release. This spalling was believed to be due to cutting the strands about 12 inches from the specimen ends in single strand specimens. Therefore, in succeeding pours the strands were cut as far from the end of a specimen as possible. The location of the beam ends adjacent to flame cutting are noted in Table 4.11.

4.8 Instrumentation and Test Procedure

Strand stress was constantly monitored using load cells at the dead end of each strand. The load cells were manufactured on-site using T-2024 aluminum and four strain gages wired in a full bridge as shown in Figure 4.11. The load cells provided measurement of the force in the strand within an accuracy of ±1 percent. Each load cell was attached to a Strain Indicator as shown in Figure 4.12 to provide instant access to strand force information.

BEAM ID	POUR #	END ADJACENT TO FLAME CUTTING
U15CD0	1	D
C15EF0	1	E
C175EF0	2	F
3C175EF2	2	F
C1625EF0	3	F
3C175EF225	3	F
3C175EF25	4	F
3C175EF225*	4	F
3C20EF275	5	F
3C20EF25	5	F
3C20EF3	6	F
6C225EF3	6	F
6C20AB275	7	A
6U20AB25	7	A

Table 4.11 Beam Ends Adjacent to Flame Cutting

Prior to release as well as at transfer, seven days and 28 days, strain readings were taken using a Whittemore type extensometer as shown in Figure 4.13. The readings immediately after transfer actually were within five hours following transfer. The readings taken prior to release were used to determine the distance between gage points before transfer. The readings immediately after transfer and at seven and 28 days also measured the distance between the gage points, however, by subtracting the initial distance the change in length between gage points could be determined. By dividing this length by the gage length, the change in concrete strain due to prestress could be determined.

The gage points were set at two inch intervals, and the extensometer measured the distance between gage points over a predetermined gage length. For pour 1 a gage length of six inches was specified, however, this produced highly variable results. For all succeeding pours a ten inch gage length was

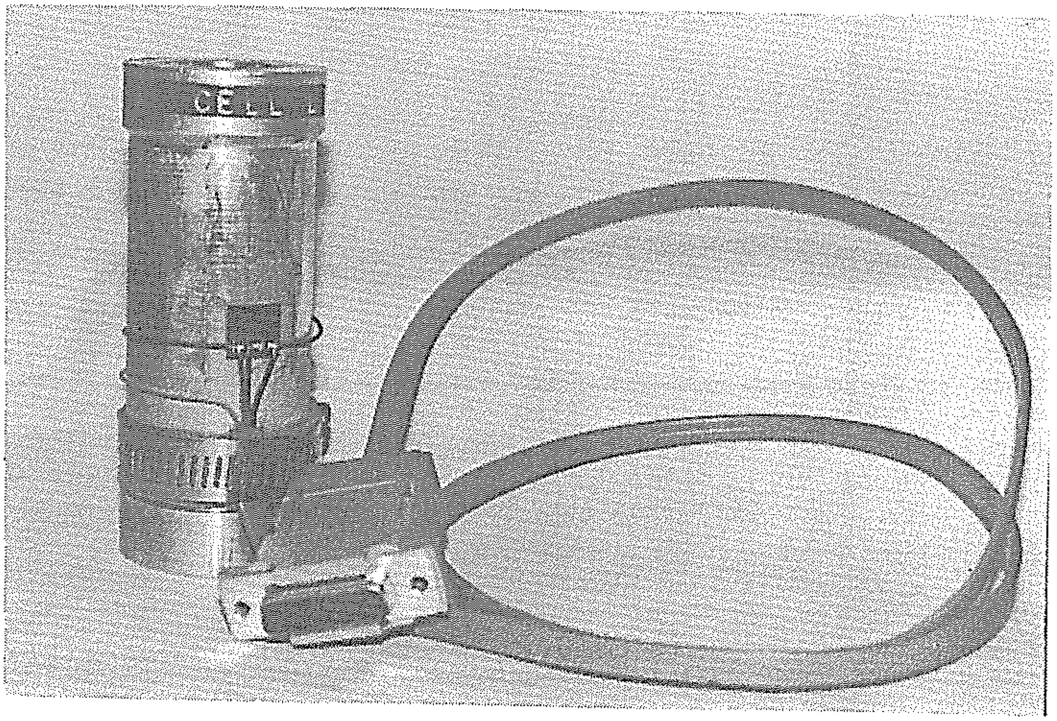


Figure 4.11 Load Cell

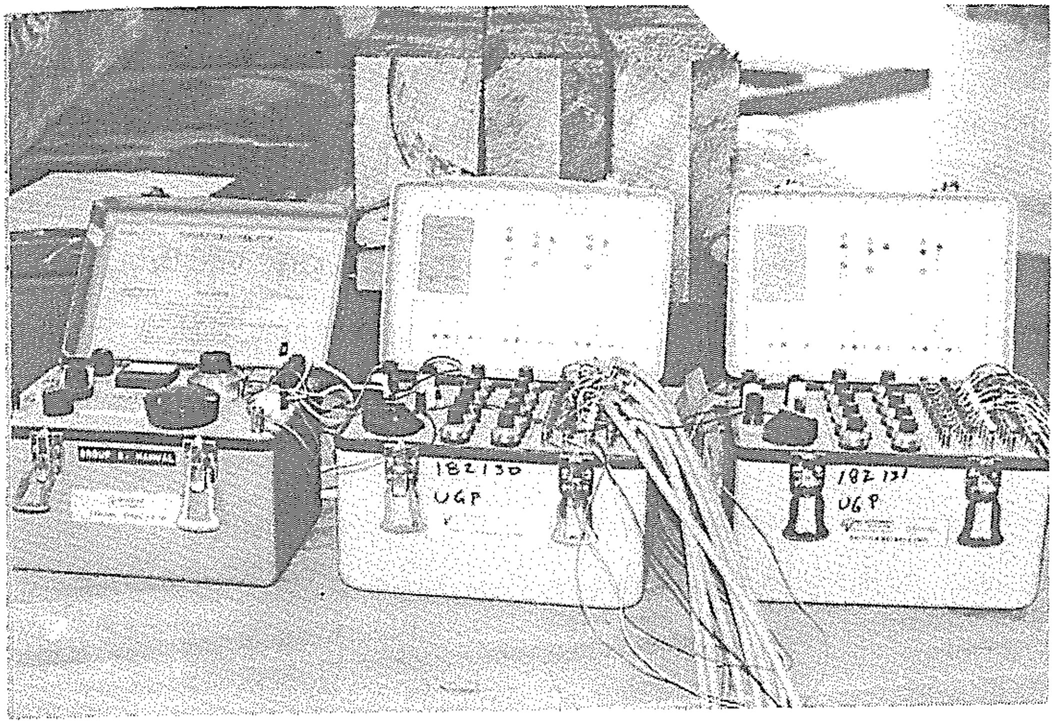


Figure 4.12 Strain Indicator

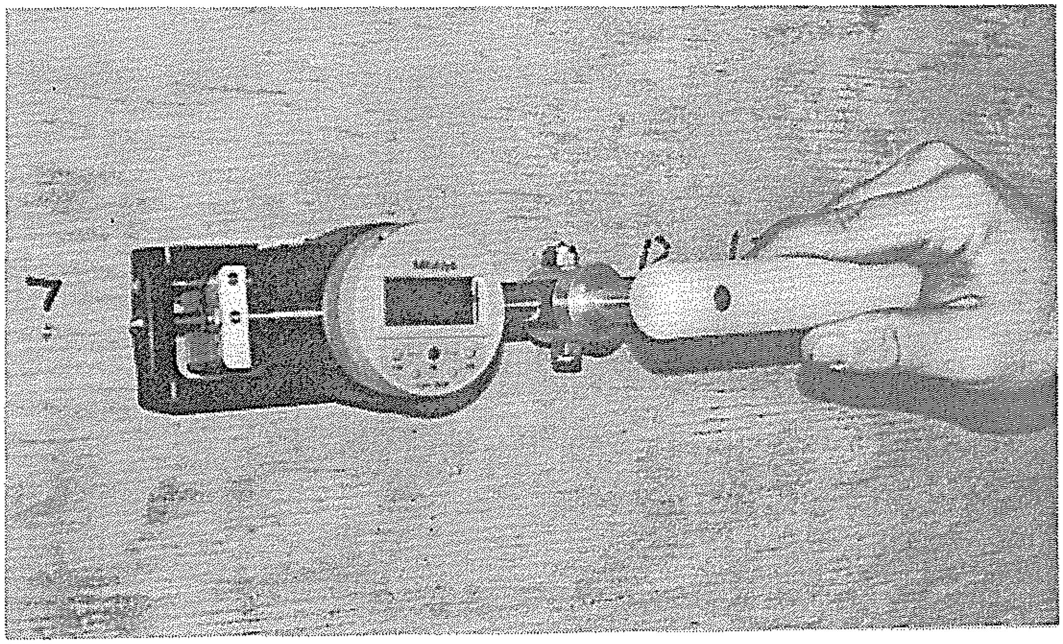


Figure 4.13 Taking Readings with Extensometer

used to increase the magnitude of the measured strain.

The extensometer provided digital readout to one ten thousandth (0.0001) of an inch. The extensometer tips did not always sit well in the gage points and this irregularity sometimes produced inconsistent results. Shrinkage, creep, and elastic strains were all included in the measurements.

In addition to strain readings, end slip readings were taken using a depth micrometer and end slip brackets Figure 4.14. End slip readings were taken to measure the distance each strand slipped into the concrete following transfer. End slip readings were used to predict transfer lengths and these predicted transfer lengths were compared to measured transfer lengths so that transfer length measurements could be verified. The end slip brackets were attached to each

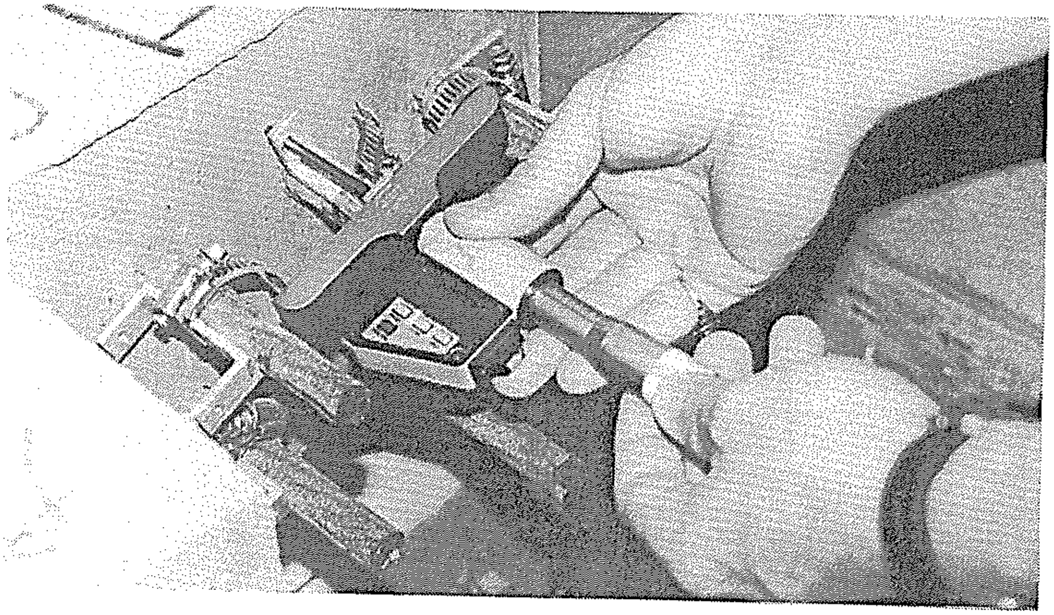


Figure 4.14 Taking Readings With Depth Micrometer

strand prior to transfer.

Some strands were not fitted with end slip brackets because end blocks, formwork, or splice chucks did not allow room for the depth micrometer to operate, therefore, no data was obtained from these strands. The distance from the end of the bracket to the specimen was measured by putting the shaft of the depth micrometer through the two small holes in the end slip bracket until the body of the micrometer was flush with the bracket, then moving the shaft up against the specimen. End slip measurements were made before and after transfer at the same time concrete strain readings were made. End slip measurements were taken from a digital readout measuring to the nearest 0.00005 inch.

After each transfer, the crack patterns of beams were analyzed and sketches were made of each end of each beam with cracks. Cracks were shown on each sketch and if propagation down the beam occurred this was noted on the sketch as well.

CHAPTER 5

Results and Analysis

5.1 Presentation of Results

The transfer length is the length over which the force in the prestressing strand is transferred to the concrete. Within this length, the stress in the prestressing strand varies from zero to the effective stress, (f_{se}). The transfer length for each end of a member is the distance from one end of the beam to the point where the concrete strain becomes uniform and reaches its maximum.

Strain readings from all the beams were recorded in a spread sheet program. The readings were used to determine the effective concrete strain immediately following transfer, and at seven days and 28 days after transfer. This data was used to plot the effective concrete strain versus the length of each beam. The transfer length was determined by first drawing the best horizontal line through the points forming the strain plateau. The transfer length of each beam was defined as the distance from the end of the beam to the point where the concrete strain reaches the strain plateau. Therefore, the transfer length is the distance required for 100 percent of the effective stress, (f_{se}), to be transferred to the concrete. This method for defining transfer length was used so that the transfer length would not be underestimated. This method is contrary to that used by some previous researchers.[5,8,12]

Figure 5.1 illustrates the method used in this research with a representative plot of strain versus beam length. Figure 5.1 shows a strain plateau of 6.8 $\times 10^{-6}$ in/in immediately after transfer and a transfer length for end E of 30.0 inches. The transfer length of each end of each beam was determined immediately following transfer, at seven days, and at twenty-eight days. The plots of concrete strain versus distance for each beam can be found in Appendix B.

The transfer lengths recorded for all beams can be found in the tables in Appendix C. Cracked beams, as denoted by the superscript "cr" in these tables are defined as specimens which developed cracks during prestress transfer.

Specimens C15EF0 and C15GH0 split completely open and no transfer length could be determined. Specimens U15AB0, U15CD0, and C1625CD0 provided plots from which no transfer length could be determined, as the concrete strain plots for these beams showed no identifiable strain plateau. Effective concrete strain data for specimen 6C225CD275 was lost in a computer malfunction.

End slip is the distance an individual strand slips into the concrete after prestress release. End slip of each strand was determined by taking a measurement before

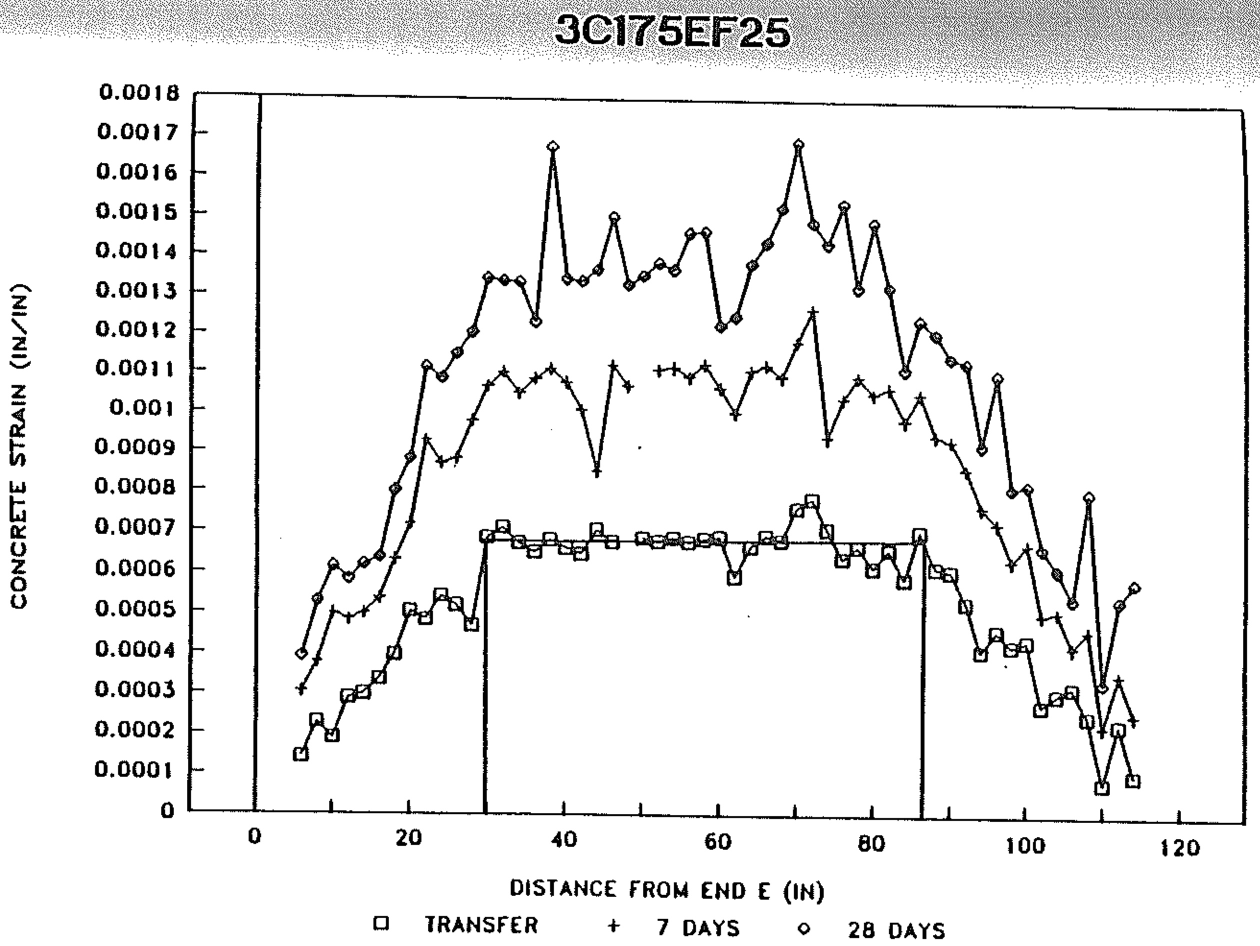


Figure 5.1 Representative Concrete Strain Plot

transfer and then after transfer and the difference of these measurements constituted the end slip. End slip measurements were taken immediately following transfer, and at seven and 28 days after transfer. End slip measurements for all specimens can be found in Appendix D. The average end slip for each end of each specimen can be found in the tables in Appendix C. Some end slip brackets were not installed or were damaged during specimen fabrication, thus, no data was obtained at these locations.

5.2 Analysis of Transfer Length Results

Table 5.1 presents the average transfer lengths from different specimen types. For clarity, all transfer length comparisons are made with transfer lengths recorded immediately after transfer unless otherwise noted. This is because the AASHTO equation for transfer length is based on transfer lengths immediately after transfer. The number of samples is the number of beam ends for each specimen type for which transfer lengths were measured. As noted in the tables in Appendix C with a subscript "t" some readings listed in the 28 day column were actually made at 49 days. This data is disregarded in Table 5.1, thus, reducing the sample numbers for the 28 day column.

The standard deviations indicate the amount of scatter obtained in transfer length measurements for different specimen types. For the specimens with uncoated strand and the cracked specimens with coated strand there was a higher degree of scatter than for the non-cracked specimens with coated strand. The scatter of the cracked specimens with coated strand can be attributed to the variable amount of cracking since a high amount of cracking produced longer transfer lengths than specimens with minimal cracking. There is no speculation as to the higher degree of scatter in the uncoated strand specimens. However, it is believed a certain amount of scatter can be expected when specimens are produced with varying strand spacing, concrete cover and number of strands since these variables may effect the transfer length.

The average calculated AASHTO transfer lengths and measured transfer lengths of the beams can be found in Table 5.2. Transfer lengths were calculated based on the portion of the AASHTO[11] equation for develpment length which predicts transfer length yields the following:

$$Transfer\ Length = \frac{f_{se}}{3} d_b \qquad (5\text{-}1)$$

Where: f_{se} = Effective prestress immediately following transfer
d_b = Diameter of prestressing strand

To obtain the effective prestress, (f_{se}), immediately following transfer the following equation was used:

$$f_{se} = f_{pp} - (d\varepsilon_c)\ (E_p) \qquad (5\text{-}2)$$

Specimen Type	# In Sample	Average Transfer Length (in.)/Standard Deviation		
		Transfer	7 Days	28 Days
Uncoated (Not Cracked)	18	58.2 / 9.72	59.5 / 8.50	61.9 / 8.43 [a]
Coated Cracked	27	37.2 / 10.31	40.3 / 9.49	42.0 / 8.57 [b]
Coated Not Cracked	23	24.0 / 5.35	25.6 / 5.42	27.7 / 5.72 [c]

[a] 14 Specimens in Sample, [b] 23 Specimens in Sample, [c] 21 Specimens in Sample

Table 5.1 Average Transfer Lengths

Specimen Type	Transfer Length (in.)		Ratio Measured/AASHTO
	Measured at Transfer	Calculated*	
Uncoated (Not Cracked)	58.2	31.2	1.87
Coated Cracked	37.2	31.3	1.19
Coated Not Cracked	24.0	31.7	0.76

*: by portion of AASHTO development length equation predicted transfer length

Table 5.2 AASHTO Calculated and Measured Transfer Lengths

Where: f_{pp} = Stress in strand before pouring

$d\epsilon_c$ = Average change in strain in concrete

E_p = Modulus of Elasticity of Steel ≐ 28,600 Ksi

The average change in strain, ($d\epsilon_c$), multiplied by the Modulus of Elasticity, (E_p), represents the estimated prestress losses of one day including elastic shortening, creep, and shrinkage. This method of determining f_{se} is discussed earlier in section 4.5 where f_{se} is used in checking strand and average concrete compressive stresses. The calculated transfer lengths based on the AASHTO equation and corresponding f_{se} can be found in Appendix E.

Transfer lengths for uncracked specimen ends adjacent to flame cutting did not show any significant measurable difference from transfer lengths of uncracked specimen ends not adjacent to flame cutting. This is contrary to results from other researchers.[5,8,12]

Average transfer lengths obtained from specimens with uncoated strand were greater than transfer lengths obtained in previous research of one-half inch uncoated strand.[5,6,9,10,12] However, the transfer lengths for uncoated strand specimens closely agree with results from Cousins, Johnston, and Zia.[4] This difference may be a result of the different methods of transfer length determination employed by the different researchers.

Average transfer lengths obtained for specimens with epoxy coated strand are slightly less than those recorded by

Dorsten, Hunt, and Preston[9] and are slightly higher than results of Cousins, Johnston, and Zia.[4]

5.2.1 Results for Uncoated Strand

5.2.1.1 Transfer Length of Uncoated Strand

As Table 5.1 indicates the average transfer length of the specimens with uncoated strand at transfer is 58.2 inches or approximately 116 strand diameters. There is an increase in transfer length of about 6 percent from transfer to 28 days, and none of the uncoated samples cracked at transfer.

Comparison of transfer lengths in Table 5.2 shows that the portion of the AASHTO equation for development which predicts transfer lengths[11] underestimate by approximately 90 percent the measured transfer length. Tables 5.3, 5.4, and 5.5 show the average transfer length versus concrete cover, strand spacing, and number of strands

Cover (in.)	Average Transfer Length (in.) / # Samples
1.625	47.0 / 2
1.750	62.7 / 10
2.000	60.0 / 4
2.250	43.0 / 2

Table 5.3 Average Transfer Lengths of Uncoated Strand vs. Concrete Cover

respectively. It appears that increasing spacing and/or cover may decrease transfer length. The only specimens that do not fit this trend are the single strand specimens with a cover of 1.625 inches (Table 5.3), and the single strand specimens of Table 5.5. This is contrary to previous research which has shown that increasing spacing has little effect on transfer length.[12] The effect of number of strands on the transfer length was not conclusive.

Center to Center Spacing (in.)	Average Transfer Length (in.) / # Samples
2.00	67.0 / 2
2.25	60.8 / 4
2.50	59.3 / 6
3.00	43.0 / 2

Table 5.4 Average Transfer Lengths of Uncoated Strand vs. Center to Center Spacing

Number of Strands	Average Transfer Length (in.) / # Samples
1	57.0 / 4
3	62.5 / 10
6	48.5 / 4

Table 5.5 Average Transfer Lengths of Uncoated Strand vs. Number of Strand

5.2.1.2 Required Spacing of Uncoated Strand

AASHTO 9.25.2.1 requires a minimum clear spacing of three times the diameter of the strand or 1⅓ times the maximum size of the concrete aggregate, whichever is greater.[11] Therefore, for the one-half inch diameter prestressing strand in these tests the minimum center to center spacing is 2.0 inches. All specimens with uncoated strand including those with 2.0 inches center to center spacing did not experience cracking. Thus, the 2.0 inches spacing requirement is valid.

5.2.1.3 Required Concrete Cover of Uncoated Strand

AASHTO 9.25.1.1 requires a minimum clear concrete cover of 1.5 inches for prestressing strand.[11] These requirements are necessary to prevent cracking of prestressed members at transfer and to protect the prestressing strand from corrosion. Specimens U15AB0 and U15CD0 each had ends which did not crack and thus met the AASHTO requirements for concrete cover. It is believed the cracking of ends B and C of specimens U15AB0 and U15CD0, respectively, was due to flame cutting the strand to close to the beam ends causing a violent increase in strand swell at the beam ends. Each end spalled off and didn't develop a crack pattern like other cracked beams. Unay, Russel, Burns, and Kreger[12] also experienced violent specimen movement with conventional flame cutting of single strand specimens. Thus, the cracking is probably not due to cover requirements. It appears that the AASHTO requirements for concrete cover are valid for uncoated prestressing strand.

5.2.2 Results for Coated Strand

5.2.2.1 Results for Transfer Length of Coated Strand

Table 5.1 also includes the average transfer lengths for the specimens with coated strand. This data was divided into two categories, non-cracked specimens and cracked specimens, to facilitate transfer length determination in noncracked specimens. As expected cracked specimens developed longer transfer lengths than noncracked specimens. The ratio of measured transfer length to AASHTO calculated transfer lengths, as shown in Table 5.2 is 1.19 for the coated cracked specimens and 0.76 for the coated noncracked specimens. This shows that the AASHTO equation predicted transfer lengths are slightly conservative for coated strand specimens with no cracking.

When cracking occurred at prestress transfer the transfer lengths increased because the bond between the concrete and strand was weakened within the cracked area. Cracked beams developed either spacing cracks or both spacing and cover cracks. Spacing cracks were defined as cracks occurring between strands while cover cracks were those which propagated from the strands to the outside edge of the specimen. Cracking began at the specimen end and cover cracks sometimes extended down the beam as much as 4½ feet. The transfer length of specimens with epoxy coated strand that cracked appear to approach the average transfer length of the uncracked specimens (24.0 in.) with increasing cover and spacing.

5.2.2.1.1 Effect of Concrete Cover on Transfer Length of Coated Strand

Table 5.6 shows the average transfer lengths of coated strand versus concrete cover. The average transfer length of all coated specimens versus cover is graphically represented in Figure 5.2 which indicates an indirect relationship between concrete cover and transfer length. As cover increases the transfer length decreases. The exception is the initial average transfer length of 26.0 inches occurring with a cover of 1.625 inches. This bar represents only two single strand specimens while the remainder of the chart represents single, three, and six strand arrangements.

Cover (in.)	Average Transfer Length (in.) / # Samples		
	Cracked Only	Not Cracked Only	Both
1.625	- / 0	26.0 / 2	26.0 / 2
1.750	39.1 / 16	22.0 / 4	35.7 / 20
2.000	37.0 / 8	26.8 / 6	32.6 / 14
2.250	27.7 / 3	22.7 / 11	23.8 / 14

Table 5.6 Average Transfer Lengths of Coated Strand vs. Concrete Cover

Observing the data in Table 5.6 for average transfer lengths of cracked specimens only it appears that the transfer length decreased as cover increased, thus

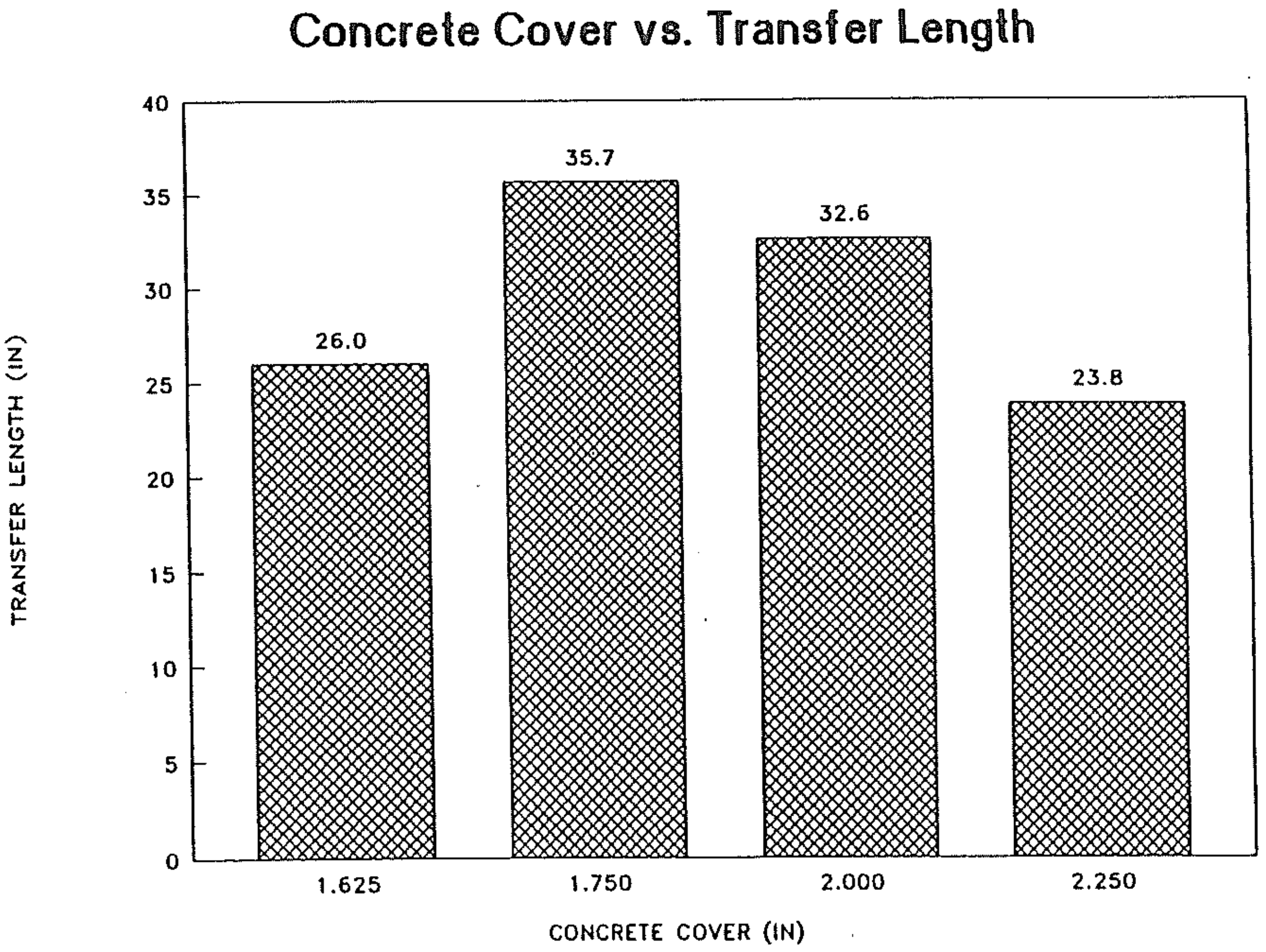


Figure 5.2 Graphic Representation of Concrete Cover and Transfer Length Relationship

supporting the indirect relationship between cover and transfer length. In agreement with this idea is the fact that crack lengths along the beam decreased as the concrete cover increased.

5.2.2.1.2 Effect of Strand Spacing on Transfer Length of Coated Strand

The average transfer lengths versus strand spacing are shown in Table 5.7 and a graphical representation of all coated strand specimen spacings versus transfer length is shown in Figure 5.3. As is the case with cover and transfer length there is a relationship between spacing and transfer length. Transfer length for only the cracked sections appears to decrease and level out with an increase in strand spacing. The average transfer length of coated specimens with a cover of 3.0 inches is misleading as it takes into effect specimen 3C20EF3 which provided a relatively high transfer length of 55 inches at end F.

Center to Center Spacing (in.)	Average Transfer Length (in.) / # Samples		
	Cracked Only	Not Cracked Only	Both
2.00	46.5 / 4	-	46.5 / 4
2.25	38.8 / 8	-	38.8 / 8
2.50	34.1 / 7	22.4 / 5	29.3 / 12
2.75	32.8 / 4	24.3 / 6	27.7 / 10
3.00	34.5 / 4	25.5 / 6	29.1 / 10

Table 5.7 Average Transfer Lengths of Coated Strand vs. Strand Spacing

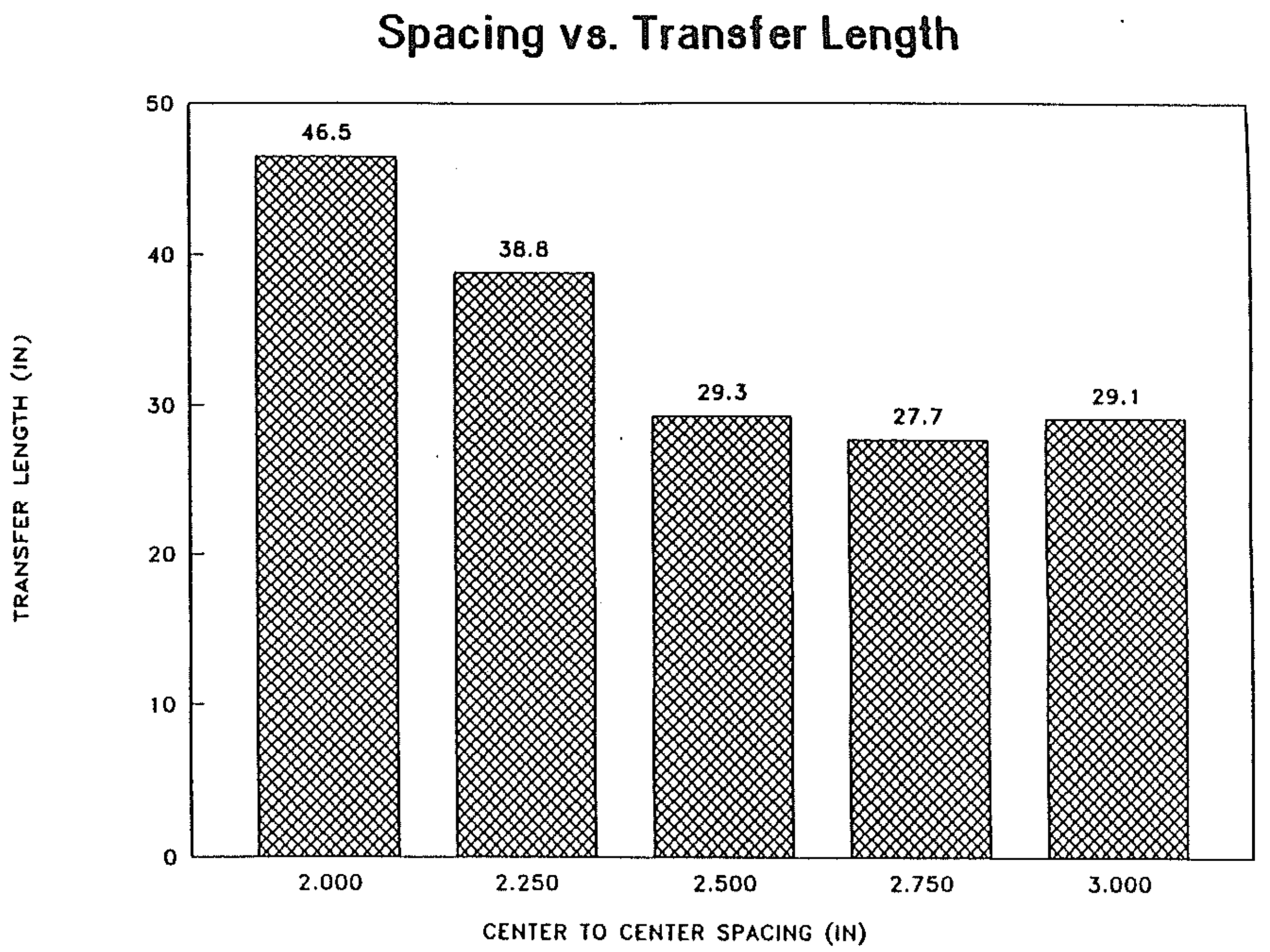


Figure 5.3 Graphic Representation of Strand Spacing and Transfer Length Relationship

Without including this data the average transfer length of coated specimens with 3.0 inches center to center spacing would be 26.22 inches. Regardless, Figure 5.3 does show that a relationship exists between center to center spacing and transfer length. As center to center spacing increases the transfer length decreases. This idea is also supported by the crack patterns as an increase in center to center spacing decreased the number as well as length of cracks appearing in a specimen.

5.2.2.1.3 Effect of Number of Strands on Transfer Length of Coated Strand

Transfer length data was not obtained for any cracked single strand specimens, and no six strand specimens cracked. As Table 5.8 indicates there is a minimal increases in transfer length with an increase in number of coated strands. However due to the accuracy of transfer length determinations it is assumed that an increase in number of strands does not affect transfer length significantly.

Number of Strands	Average Transfer Length (in.) / # Samples		
	Cracked Only	Not Cracked Only	Both
1	- / 0	23.3 / 6	23.3 / 6
3	38.7 / 29	23.8 / 5	36.6 / 34
6	- / 0	24.3 / 12	24.3 / 12

Table 5.8 Average Transfer Lengths of Coated Strand vs. Number of Strands

5.2.2.2 Spacing Requirements for Coated Strand

AASHTO 9.25.2.1 recommends a minimum center to center spacing for on-half inch diameter strand of 2.0 inches.[11] However the specimens with a 2.0 inch center to center spacing experienced considerable cracking including spacing cracks. The smallest observed center to center spacing of a three strand specimen with no cracking is the F end of 3C20EF25 with a center to center spacing of 2.5 inches. Specimen 3C20EF25 is one of the two specimens in which the smallest concrete cover with no cracking was obtained. Uncracked ends also occurred with strand spacings of 2.75 inches and 3 inches, however, 2.5 inches appears to be the minimum requirement for three strands in a single layer.

For the six strand arrangement two specimens with center to center spacings of 2.5 inches did not crack, 6C20CD25 and 6C225EF25. All six strand specimens with 2.5 inch center to center spacing had fully noncracked ends while many three strand specimens of equal or greater spacing experienced cracking. It appears that an additional layer of strands causes confinement and this aids in transfer and thus, crack prevention. A six strand arrangement may have a minimum spacing requirement smaller than 2.5 inches, however, the three strand arrangement experienced cracking at spacings less than 2.5 inches. The AASHTO minimum requirements for spacing were insufficient for either strand arrangement and this resulted in spacing cracks.

5.2.2.3 Concrete Cover Requirements for Coated Strand

AASHTO 9.25.1.1 recommends a minimum concrete cover of 1.5 inches for prestressing strands.[11] For single strand specimens, C15EF0 and C15GH0 met the code requirements for minimum cover, however, they both split open down each side from one end to another as is noted in Appendix G. A fully noncracked transfer was achieved with a cover of 1.625 inches in the noncracked single strand specimen C1625EF0. However, a 1.75 inch concrete cover specimen with three strand arrangement experienced cracking. In a pure cover specimen (one strand prism) a minimum cover of 1.625 inches appears to be sufficient.

The smallest concrete cover of a noncracked multiple strand specimen end occurred at the F end of specimen 3C20EF25 and at the D end of 3C20CD275, each with 2.0 inches of concrete cover. With the six strand arrangement the fully developed specimen 6C20CD25 did not crack with a concrete cover of 2.0 inches.

The addition of strand at spacings closer than twice the required cover may have contributed to cracking. The cracks in the three strand specimens with 1.75 inch concrete cover may have been caused by insufficient spacing. Spacing cracks may have occurred and propagated to the outside surface of the beam. Therefore, cover cracks may have just been extensions of the spacing cracks.

As is the case with spacing it appears an additional layer of strand aids in transfer and prevents cracking. It appears that the AASHTO requirements for concrete cover of 1.5 inches are insufficient for epoxy coated strand and different provisions for coated strand should be made.

5.2.2.4 Summary of Coated Strand Results

Transfer length of coated strand is greatly affected by concrete cover and strand spacing. There exists an indirect relationship between cover, spacing and the transfer length. Transfer length decreases with an increase in concrete cover and center to center strand spacing. The transfer lengths measured are shorter than those predicted by the AASHTO equation for transfer length. The AASHTO calculated transfer lengths are approximately 30 percent greater than those measured for epoxy coated prestressing strand in uncracked sections.

The smallest concrete cover which resulted in no cracking was 2.0 inches for multi-strand and 1.625 inches for single strand. These covers are both larger than the minimum cover required by AASHTO 9.25.1.1.[11] The smallest center to center strand spacing achieved without cracking of 2.5 inches is larger than the minimum specified by AASHTO 9.25.2.1[11] as 2.0 inches.

The AASHTO[11] requirements for concrete cover and strand spacing would not have provided enough concrete for the epoxy coated strand specimens used in this research to transfer the prestressing force without cracking. Since the specimens used in this research had no confinement reinforcement, spacing and cover requirements should be increased somewhat in pretensioned , prestressed members with no confinement. However, for bridge girders and other pretensioned, prestressed members that inherently have a significant amount of confinement reinforcement in the form of stirrups and end zone reinforcement, this may not be necessary. The confinement reinforcement would limit crack growth and decrease crack widths. The use of confinement reinforcement would probably result in transfer lengths between those in Table 5.6 and Table 5.7 for cracked and uncracked specimens.

5.3 Calculated versus Measured End Slips

The end slip of each strand can be calculated based on the concrete and steel strain data within the transfer length of each specimen.[1] This calculated end slip can then be compared to the measured end slip to verify the accuracy of the transfer length determinations. Figure 5.4 shows an idealized plot of steel strain (ϵ_s) and concrete strain (ϵ_c) along the transfer length. ϵ_{se} is the strain plateau and is derived from the following equation:

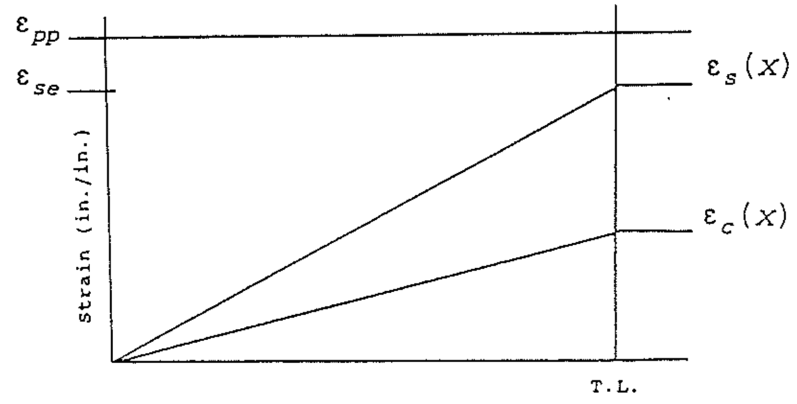
$$\epsilon_{se} = \epsilon_{pp} - d\epsilon_c \qquad (5\text{-}3)$$

Where:

ϵ_{pp} = Steel strain prior to concrete placement

$d\epsilon_c$= Average change in strain in concrete from before concrete placement to immediately following transfer

It is noted that the ($d\epsilon_c$) term in equation (5-3) is the estimated strain losses up to immediately following transfer, and is assumed as the value of the concrete strain plateau at this time. The shape of the steel strain plot is assumed to be a straight line, and proportionally the same as the concrete strain plot due to equilibrium of forces through any beam section and the assumption that perfect bond exists between the concrete and steel within the strain plateau. ϵ_{se} is the magnitude of the steel strain plateau.



T.L. = Transfer Length

Figure 5.4 Idealized Plot of Steel and Concrete Strain

This assumption results in a steel strain plot approximately ten times greater than the concrete strain plot but of the same shape. The elastic shortening (El.Sh.) over the transfer length (T.L.) of a specimen is the area under $\epsilon_c(x)$:

$$El.Sh. = \int_0^{T.L.} \varepsilon_c(x)\,dx \qquad (5\text{-}4)$$

The area between the $\epsilon_s(x)$ curve and the initial steel strain plateau, ϵ_{pp}, extended to the free end of the beam is the sum of the elastic shortening and the end slip (E.S.) or:

$$E.S. + El.Sh. = \varepsilon_{pp}(T.L.) - \int_0^{T.L.} \varepsilon_s(x)\,dx \qquad (5-5)$$

By rearranging equation (5-5) the end slip (E.S.) can be determined as follows:

$$E.S. = \varepsilon_{pp}(T.L.) - \int_0^{T.L.} [\varepsilon_s(x) + \varepsilon_c(x)]\,dx \qquad (5-6)$$

The average end slip was calculated for each specimen end with a measured transfer length. The calculated end slips of each beam end were averaged and are presented in Appendix F with the corresponding measured end slips and the ratio of the two. Table 5.9 gives the average ratios of measured to calculated end slips for different sets of beams. From the data in Table 5.9, it is clear that the measured transfer lengths are relatively accurate since the average ratio of the measured end slips to calculated end slips (derived from measured transfer lengths) is 1.016 with a standard deviation of 0.279. This amount of standard deviation can be expected when considering that the variables of concrete strength, strand surface condition, and effective stress can effect these calculations.

Specimen Description	Average Ratio Measured/Calculated End Slip - # Samples - Standard Deviation			
	1 Strand	3 Strand	6 Strand	All
Coated	0.833-5-.237	1.060-31-.274	0.828-11-.268	0.982-47-.290
Uncoated	1.086-4-.173	1.114-9-.102	1.169-3-.402	1.117-16-.210
Both	0.945-9-.173	1.072-40-.247	0.901-14-.332	1.016-63-.279

Table 5.9 Average Ratio of Measured to Calculated End Slips

5.4 Cracking of Specimens

Cracking occurred in some specimens. This occurrence has been previously seen in research by Cousins, Johnson, and Zia[4] and Dorsten, Hunt, and Preston[9] who experienced splitting of specimens with epoxy coated strand and by Deathrage and Burdette[10] who experience splitting of single uncoated strand specimens. Cracking occurred in 17 coated strand specimens with 15 of these being three strand specimens. No specimens with six strands experienced cracking. Only two uncoated strand specimens experienced cracking, which was in the form of end spalling. As expected, cracking does increase transfer length of specimens with coated strand as is noted in Table 5.1.

Primarily specimens cracked immediately as the prestressing force was released by flame cutting. However, a few specimens did not crack until approximately ten minutes after the strand had been cut. Sketches of the crack patterns were made and the length of the cover cracks measured. All sketches of cracked beams can be found in Appendix G.

As stated earlier in section 4.7, it is believed that the spalled ends of specimens U15AB0 and U15CD0 resulted from flame cutting to close to the beam ends and not from lack of concrete cover. No specimens with uncoated strands experienced cracking patterns typical of spacing and cover cracking.

Of the fifteen specimens that developed cracks, 12 experienced cover cracks in line with the strand layer on the faces containing gage points. Specimens C15EF0 and C15GH0 experienced this type of cracking to the extent of total splitting on at least one side of the face containing the gage points. From these observations there was some concern that the gage points may have encouraged crack propagation by weakening this area of the beam. However, because thorough consolidation was obtained, the gage points are of such small volume, and specimens with uncoated strands did not experience this type of cracking, it is believed this concern is unwarranted.

It appeared that cover cracks in some three coated strand specimens were an extension of spacing cracks. Few specimens that cracked experienced spacing cracks with cover cracks extending to the top and bottom of the cross section. Thus, insufficient spacing may develop spacing cracks which in turn propagate outward to form a cover crack. Cracking occurred so fast that it was difficult to determine where a crack began, what may have caused it, and what influence other cracks may have had.

It is clear that the AASHTO requirements set forth for concrete cover and strand spacing do not provide adequate concrete for epoxy coated prestressing strand to transfer strain. It does appear though that the addition of a layer, from the three to six strand arrangement, does improve transfer. Six strand epoxy coated specimens with spacings and covers identical to some three strand specimens did not crack while their three strand counterparts did, i.e. 6C20AB275 and 3C20EF275. This transfer improvement may be due to concrete confinement caused by the addition of another layer.

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

Research was conducted to determine the strand spacing and concrete cover requirements for epoxy coated prestressing strand. Additionally, the transfer length of both epoxy coated and uncoated prestressing strand was studied. Based on the results obtained the following conclusions can be made:

1.) Measured transfer lengths of epoxy coated prestressing strand were shorter than the measured transfer lengths of uncoated prestressing strand by about 40 percent.

2.) For unconfined sections AASHTO requirements for minimum concrete cover and center to center spacing were not adequate to prevent cracking of specimens with epoxy coated strand due to the shorter transfer length and higher bond stresses of epoxy coated strand.

3.) An additional layer of epoxy coated strands aided in transfer and crack prevention.

4.) The portion of the AASHTO equation for development length that predicts transfer length overestimated the measured transfer lengths by about 30 percent.

5.) The portion of the AASHTO equation for development length that predicts transfer length underestimated the measured transfer lengths of uncoated strand by about 90 percent.

6.2 Recommendations

Based on the results and conclusions drawn from this research the following recommendations are made:

1.) Until other research findings in this area are available, AASHTO requirements for minimum concrete cover and minimum center to center spacing should not be applied to unconfined specimens with epoxy coated prestressing strand. A minimum clear cover greater than 2.0 inches and a minimum center to center spacing greater than 2.5 inches would reduce or eliminate cracking.

2.) For epoxy coated strand to be used at AASHTO minimum spacing and cover, some other measure (such as confinement of reinforcement) should be provided to limit cracking.

3.) The AASHTO equation for transfer length should be amended to include the affects of, strand surface condition, material properties of steel and concrete, release methods, number of strands, and confinement. Thus, a more accurate prediction of transfer lengths of both epoxy coated and uncoated prestressing strand could be made.

4.) A thorough investigation should be made as to the effect of confinement reinforcement on transfer length, minimum concrete cover, and minimum spacing requirements of epoxy coated strand.

5.) Development length of epoxy coated prestressing strand should be investigated since epoxy coated strand behaves differently than uncoated strand.

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APPENDIX A

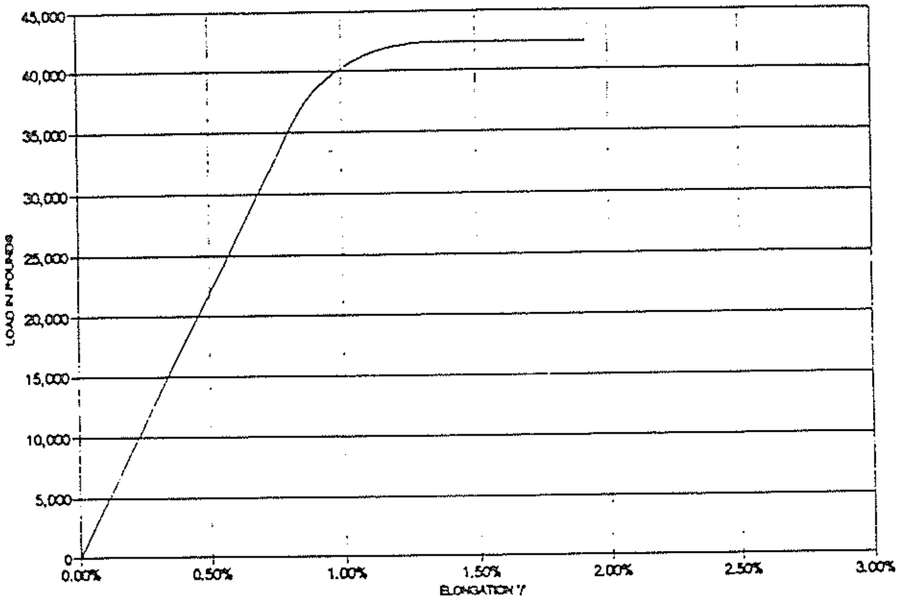
PRESTRESSING STEEL TEST DATA

TELEPHONE (904) 781-9224
TELEX NO. 81788
TELECOPY (904) 781-9224
OR (904) 783-3094

FLORIDA WIRE AND CABLE COMPANY
825 NORTH LANE AVENUE · P. O. BOX 6835 · JACKSONVILLE, FLORIDA 32236

S.A.# 01013

TEST NO. 8173


TYPICAL LOAD ELONGATION CURVE
1/2 270 KSI LO-LAX

BREAKING LOAD 43,505 Lbs
LOAD @ 1% EXT. 40,447 Lbs
ULT. ELONGATION 5.09 %
NOMINAL AREA 0.153 in^2
M.O.E. 28,600,000 p.s.i.

GUARANTEED ULT. BREAK. STRGTH. OF 41,300 POUNDS
COIL# 873012
ELONG. at 30,975 .00708 in./in.
or in 10 ft. .850 inches

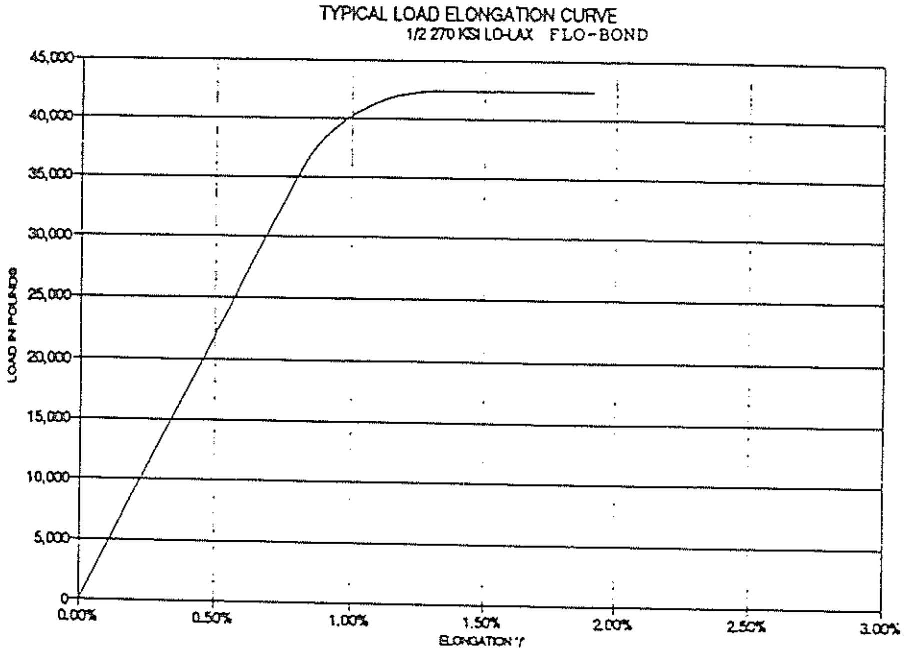
Prestressing Steel Data for Spool 1 of Uncoated Strand

TELEPHONE (904) 781-8224
TELEX NO 5[illegible]664
TELECOPY (904) 781-9234
OR (904) 783-3084

FLORIDA WIRE AND CABLE COMPANY
825 NORTH LANE AVENUE · P. O. BOX 6835 · JACKSONVILLE FLORIDA 32236

S.A.# 01013

TEST NO. 7630



BREAKING LOAD	43,505	Lbs
LOAD @ 1% EXT.	40,447	Lbs
ULT. ELONGATION	5.09	%
NOMINAL AREA	0.153	in^2
M.O.E.	28,600,000	p.s.i.

GUARANTEED ULT. BREAK. STRGTH. OF 41,300 POUNDS
COIL# 785003-387
ELONG. at 30,975 .00708 in./in.
or in 10 ft. .850 inches

Prestressing Steel Data for Spool 1 of Coated Strand

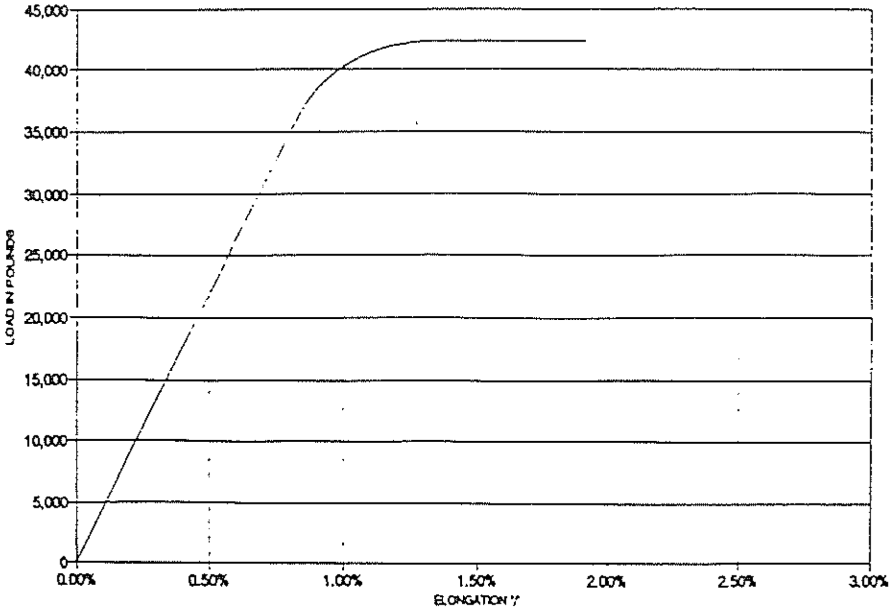
TELEPHONE 904 78[illegible]-5224
TELEX NO [illegible]
TELECOPY (904 78[illegible]-9224
OR (904) 783-3084

FLORIDA WIRE AND CABLE COMPANY
825 NORTH LANE AVENUE • [illegible] • JACKSONVILLE, FLORIDA [illegible]

S.A.# 01013

TEST NO. 11112

TYPICAL LOAD ELONGATION CURVE
1/2 270 KSI LO-LAX



BREAKING LOAD	43,505	Lbs
LOAD @ 1% EXT.	40,447	Lbs
ULT. ELONGATION	5.09	%
NOMINAL AREA	0.153	in^2
M.O.E.	28,600,000	p.s.i.

GUARANTEED ULT. BREAK. STRGTH. OF 41,300 POUNDS

COIL# 805832-426 ELONG. at 30,975 .00708 in./in.

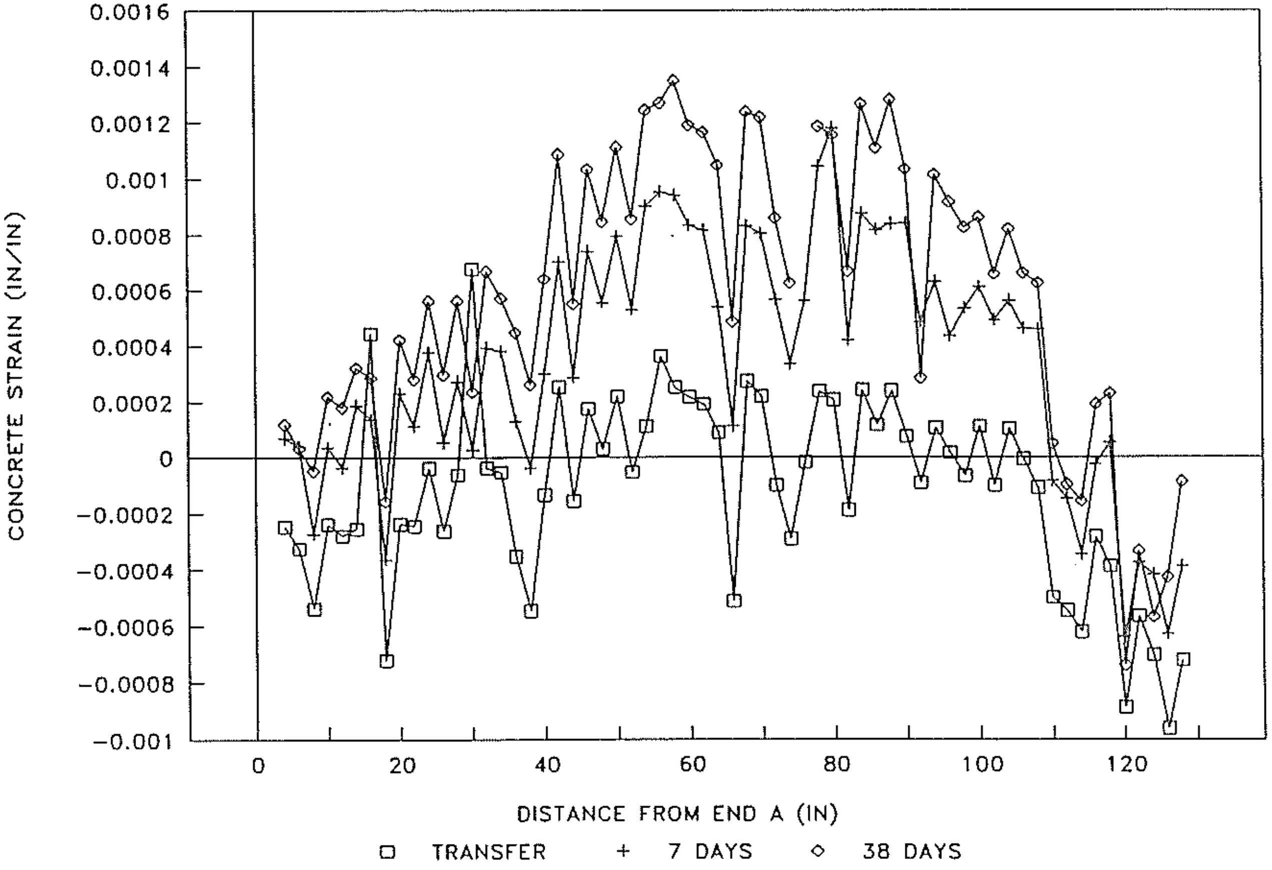
or in 10 ft. .850 inches

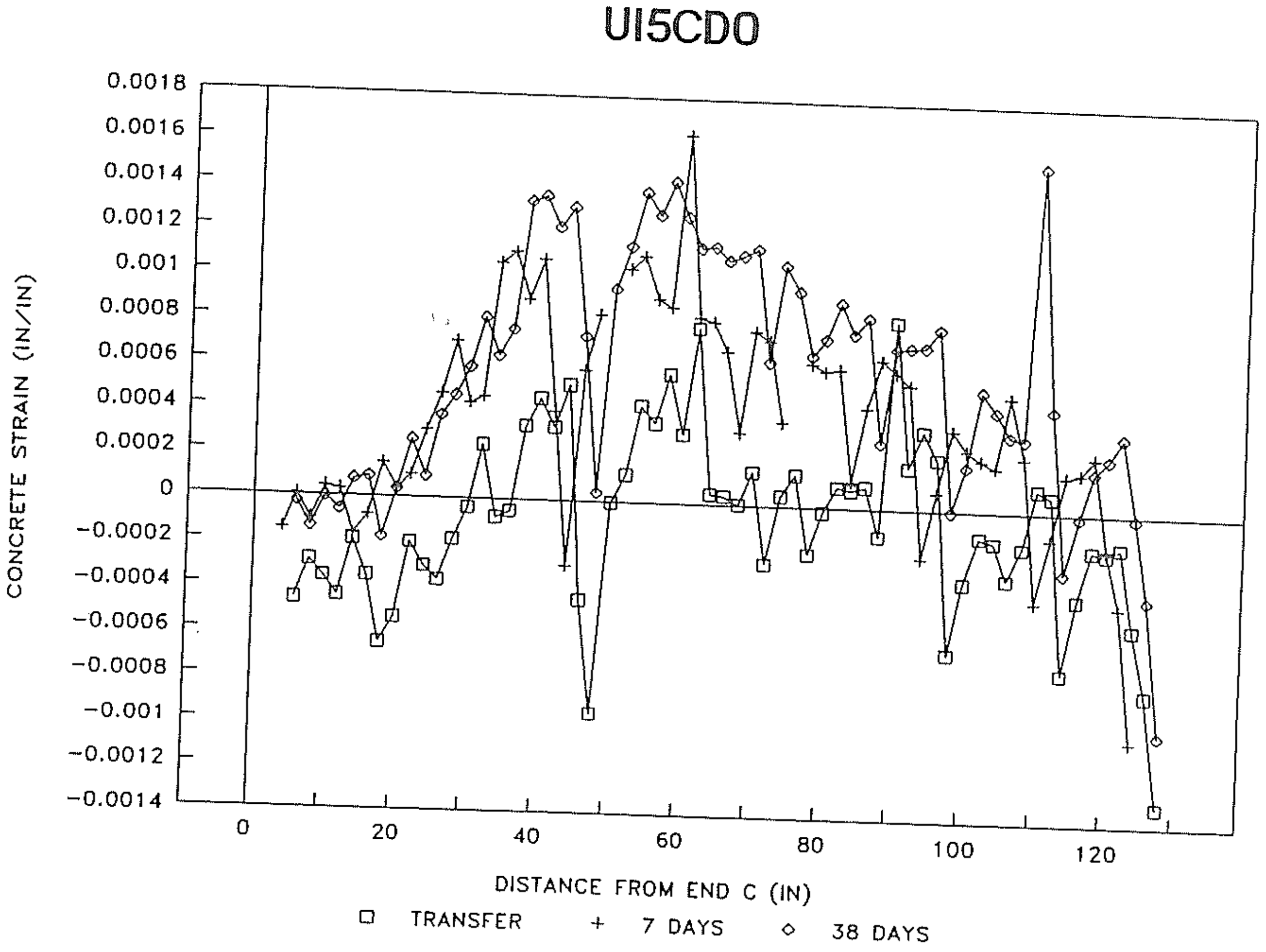
Prestressing Steel Data for Spool 2 of Coated Strand

APPENDIX B

PLOTS OF CONCRETE STRAIN VERSUS DISTANCE ALONG BEAM

UI5AB0


0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
−0.0002
−0.0004
−0.0006
−0.0008
−0.001
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 38 DAYS


UI5CDO
CONCRETE STRAIN (IN/IN)
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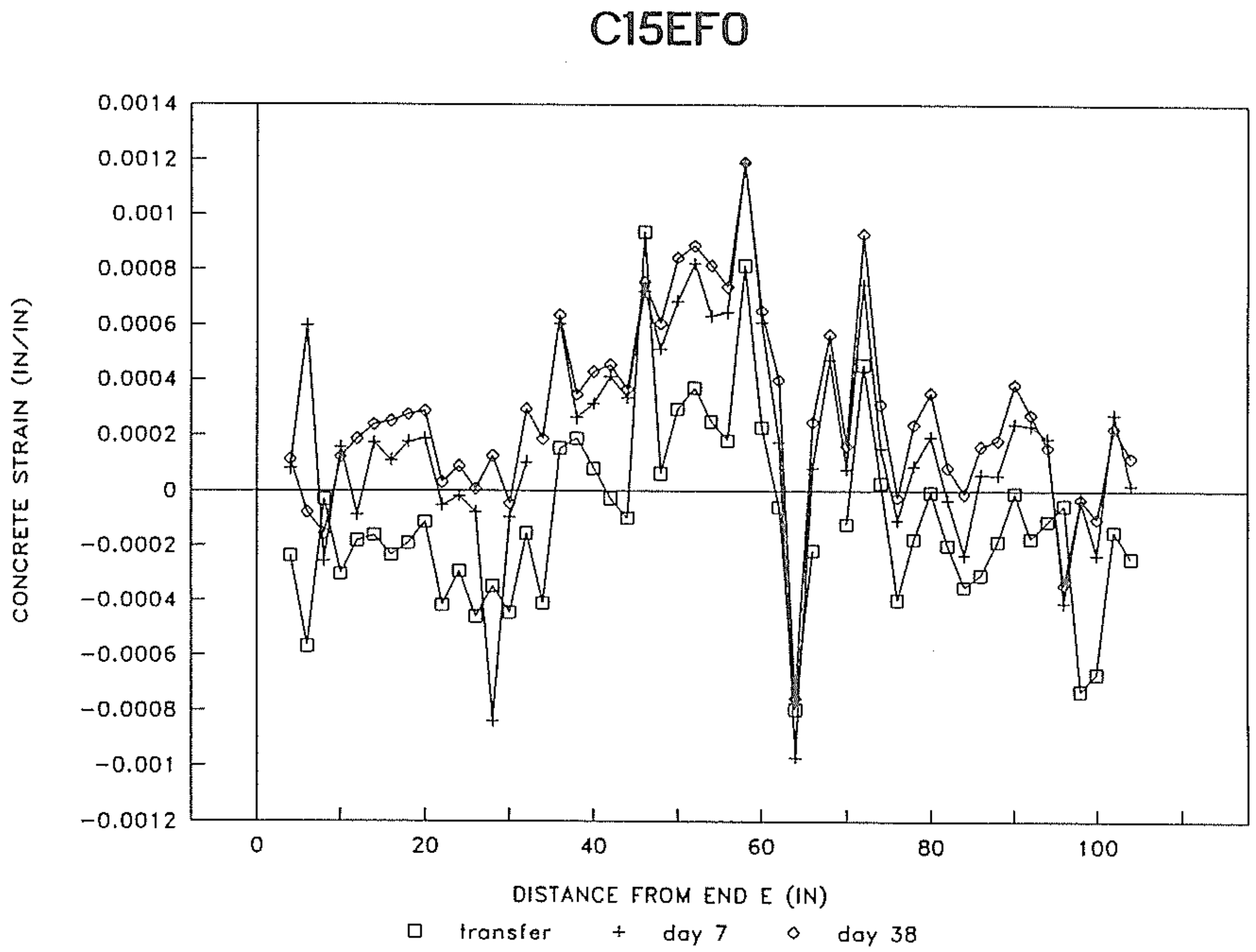
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
−0.0002
−0.0004
−0.0006
−0.0008
−0.001
−0.0012
−0.0014
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 38 DAYS


C15EF0
CONCRETE STRAIN (IN/IN)
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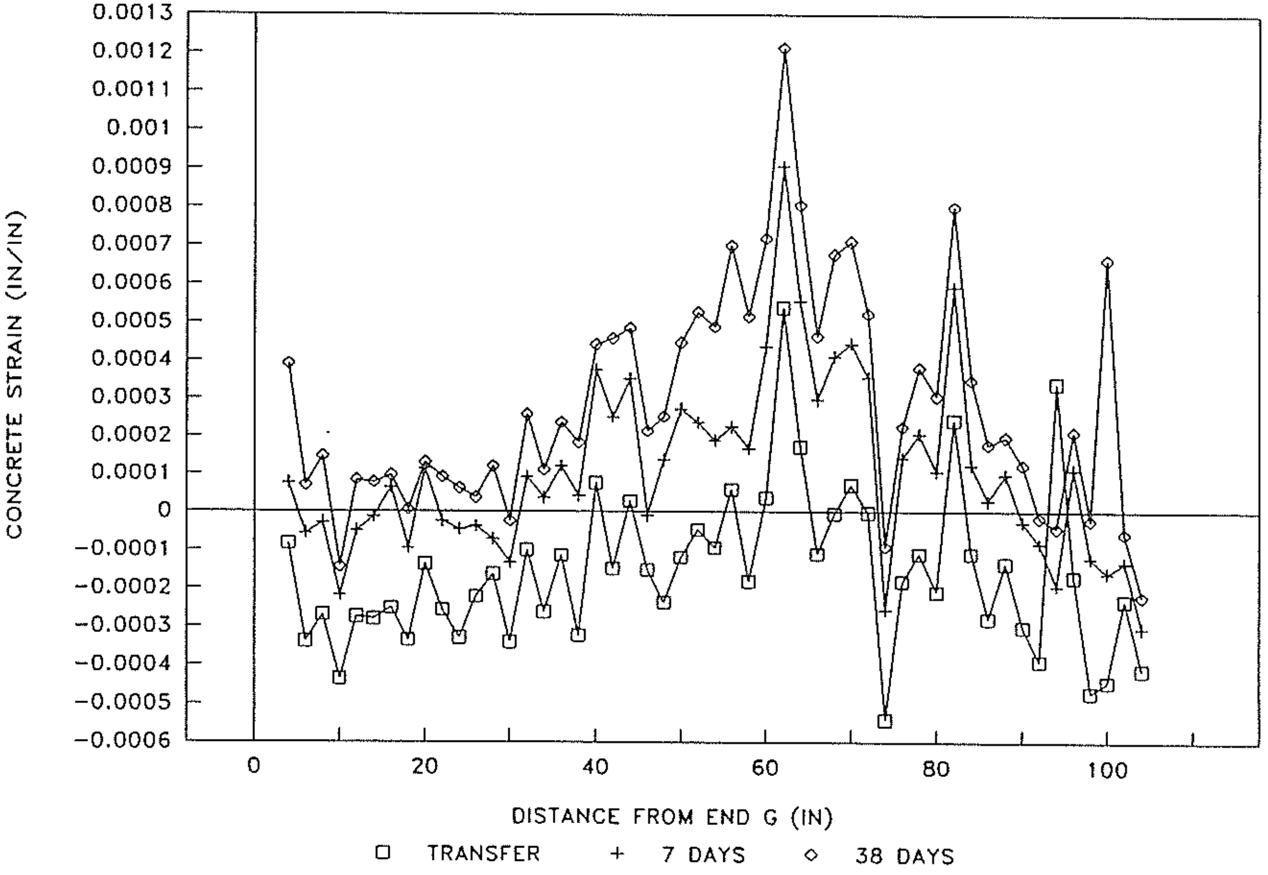
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
−0.0002
−0.0004
−0.0006
−0.0008
−0.001
−0.0012
0
20
40
60
80
100
DISTANCE FROM END E (IN)
□ transfer
+ day 7
◇ day 38

C15GHO


CONCRETE STRAIN (IN/IN)
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0.0012
0.0011
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0.0009
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0.0007
0.0006
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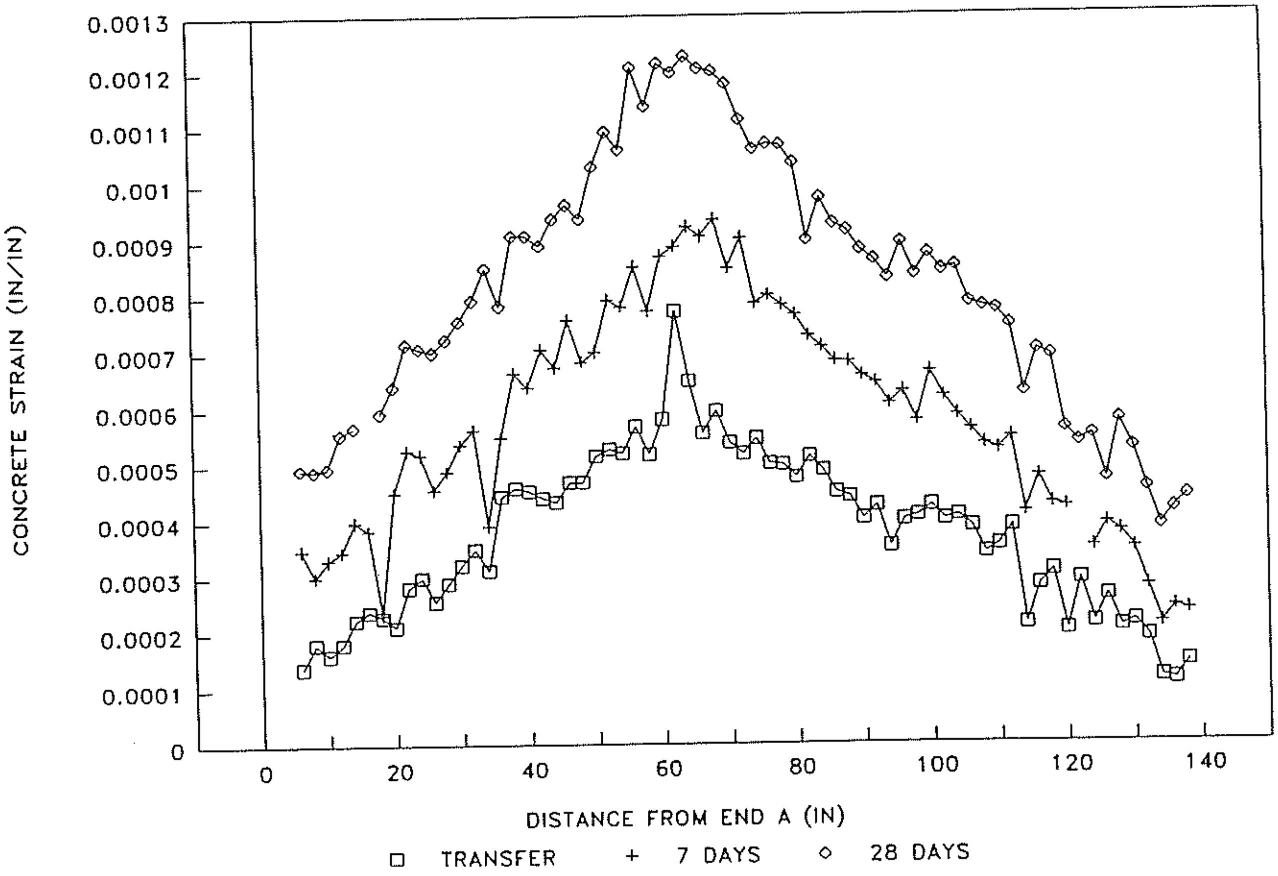
0.0004
0.0003
0.0002
0.0001
0
−0.0001
−0.0002
−0.0003
−0.0004
−0.0005
−0.0006
0
20
40
60
80
100
DISTANCE FROM END G (IN)
□ TRANSFER
+ 7 DAYS
◇ 38 DAYS

U175AB0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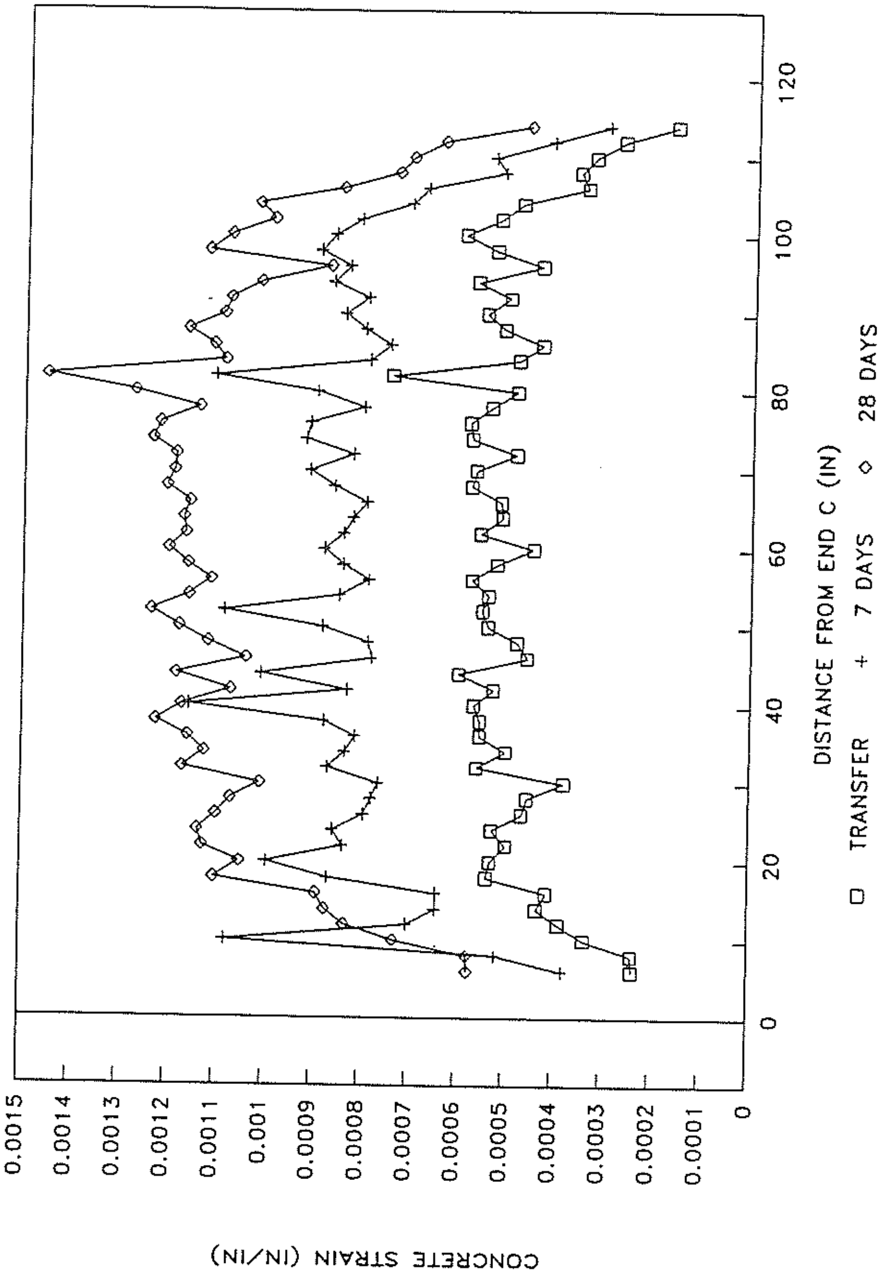
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

C175CD0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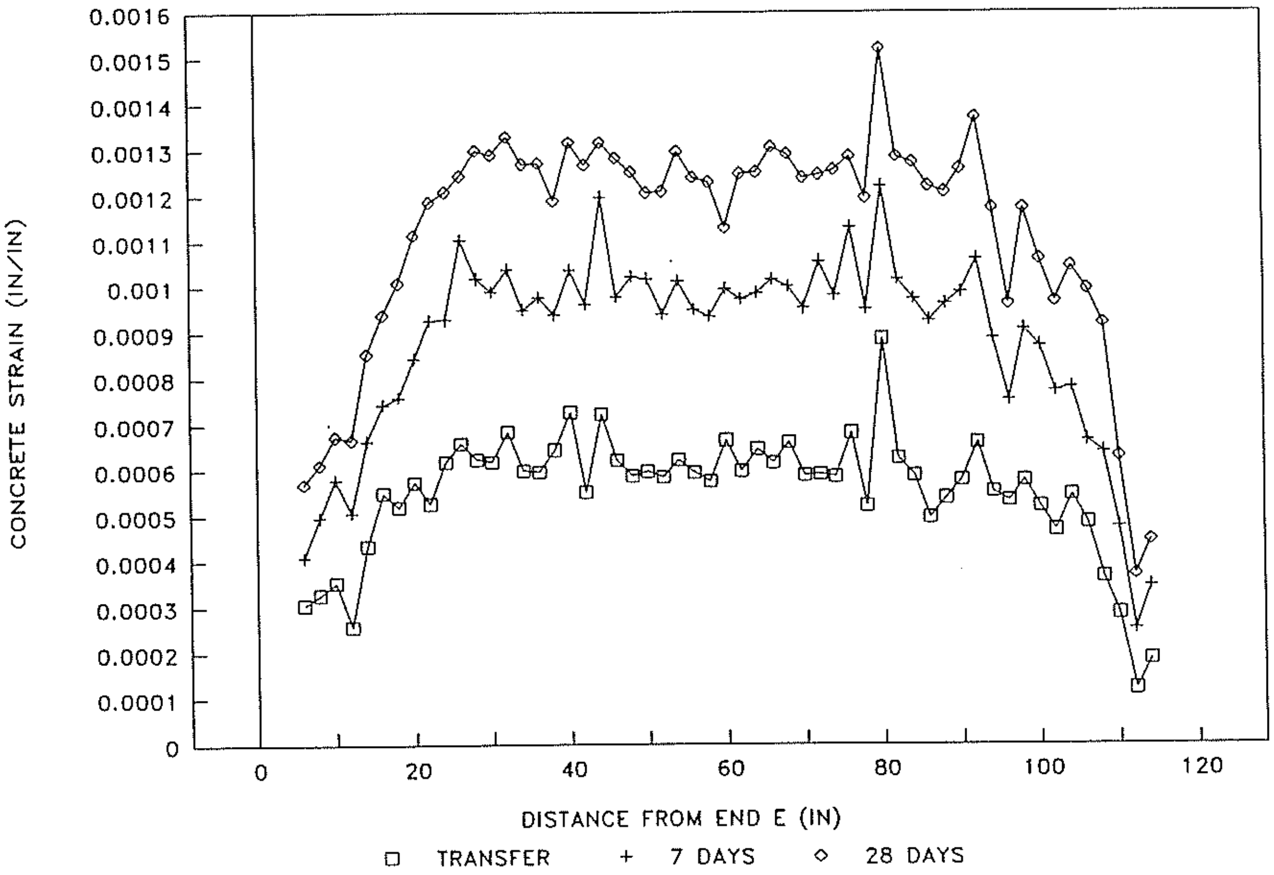
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER + 7 DAYS ◇ 28 DAYS

C175EF0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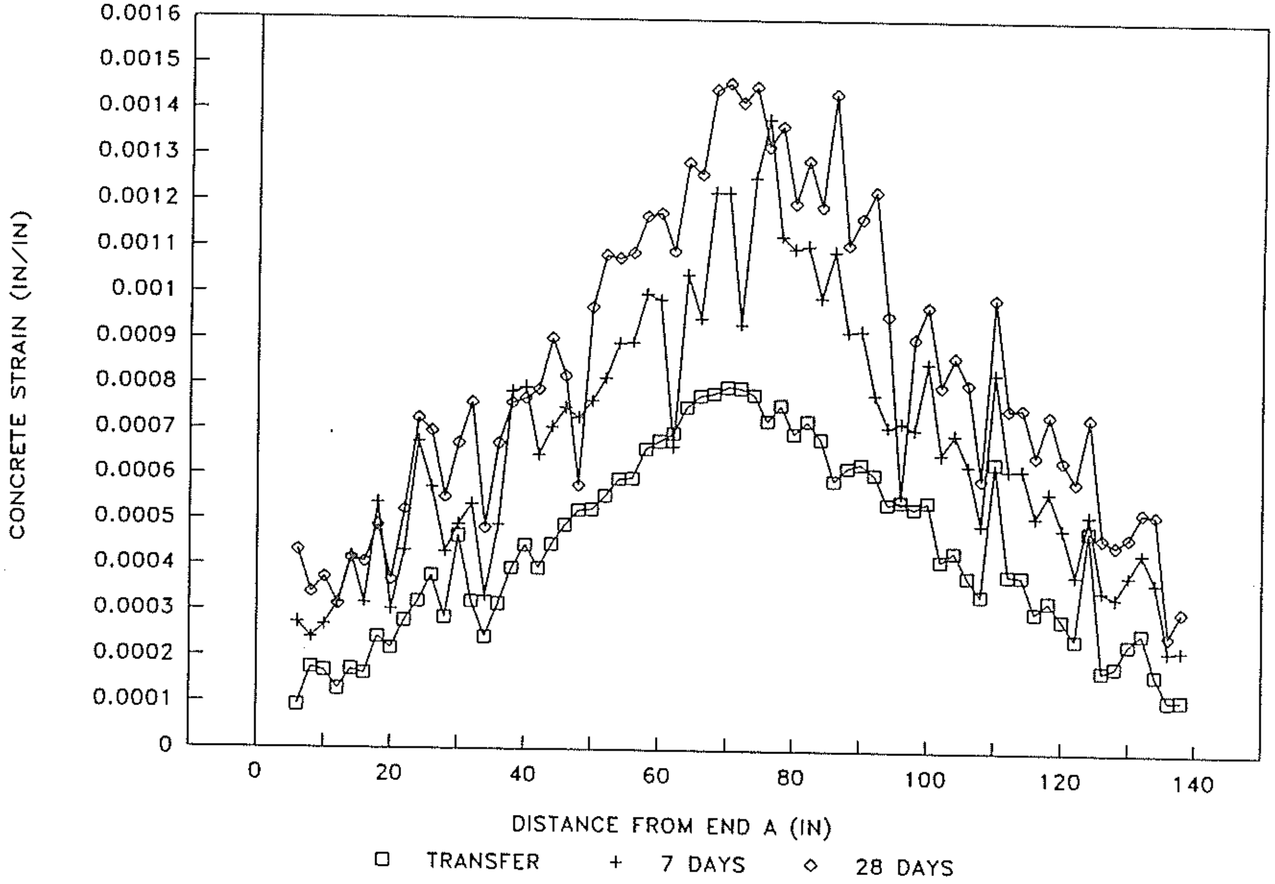
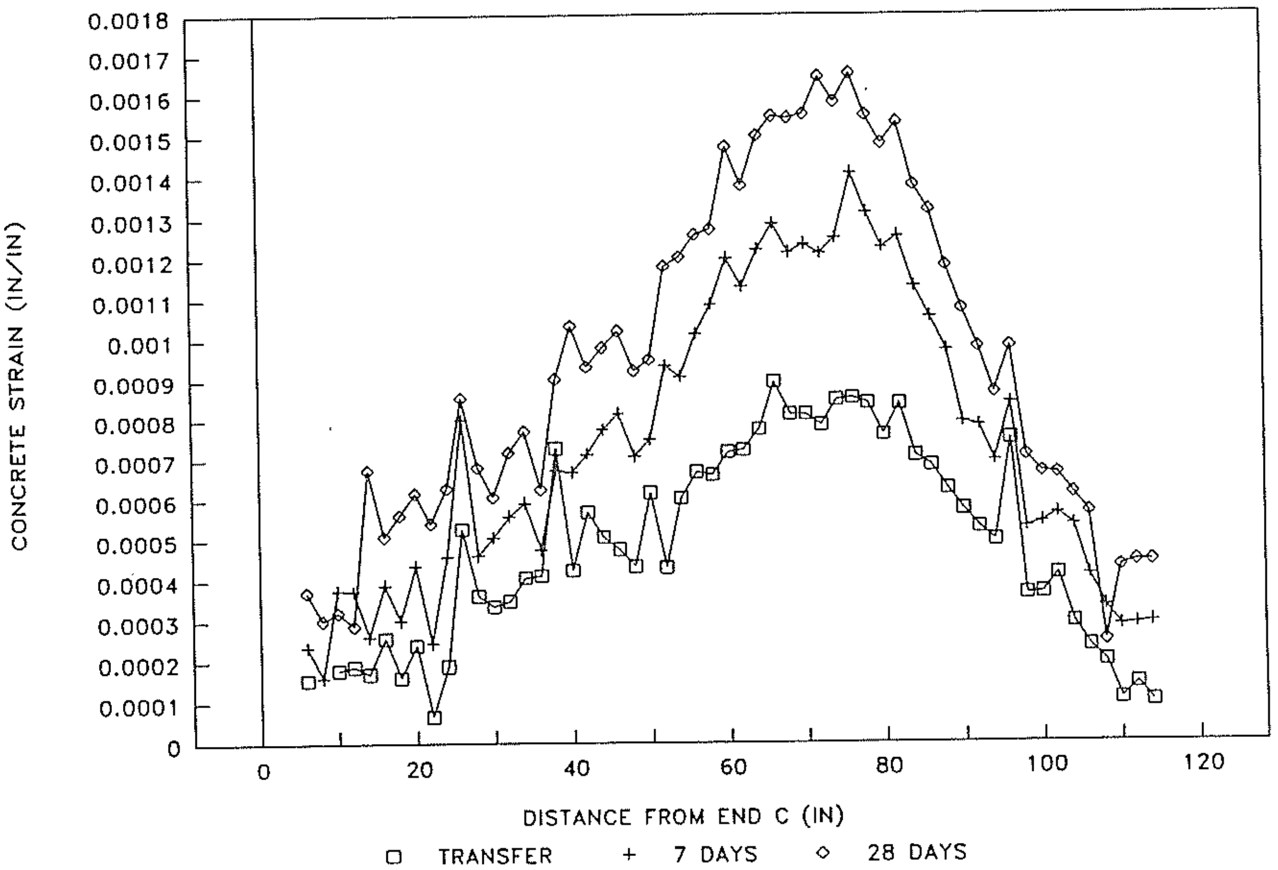
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS



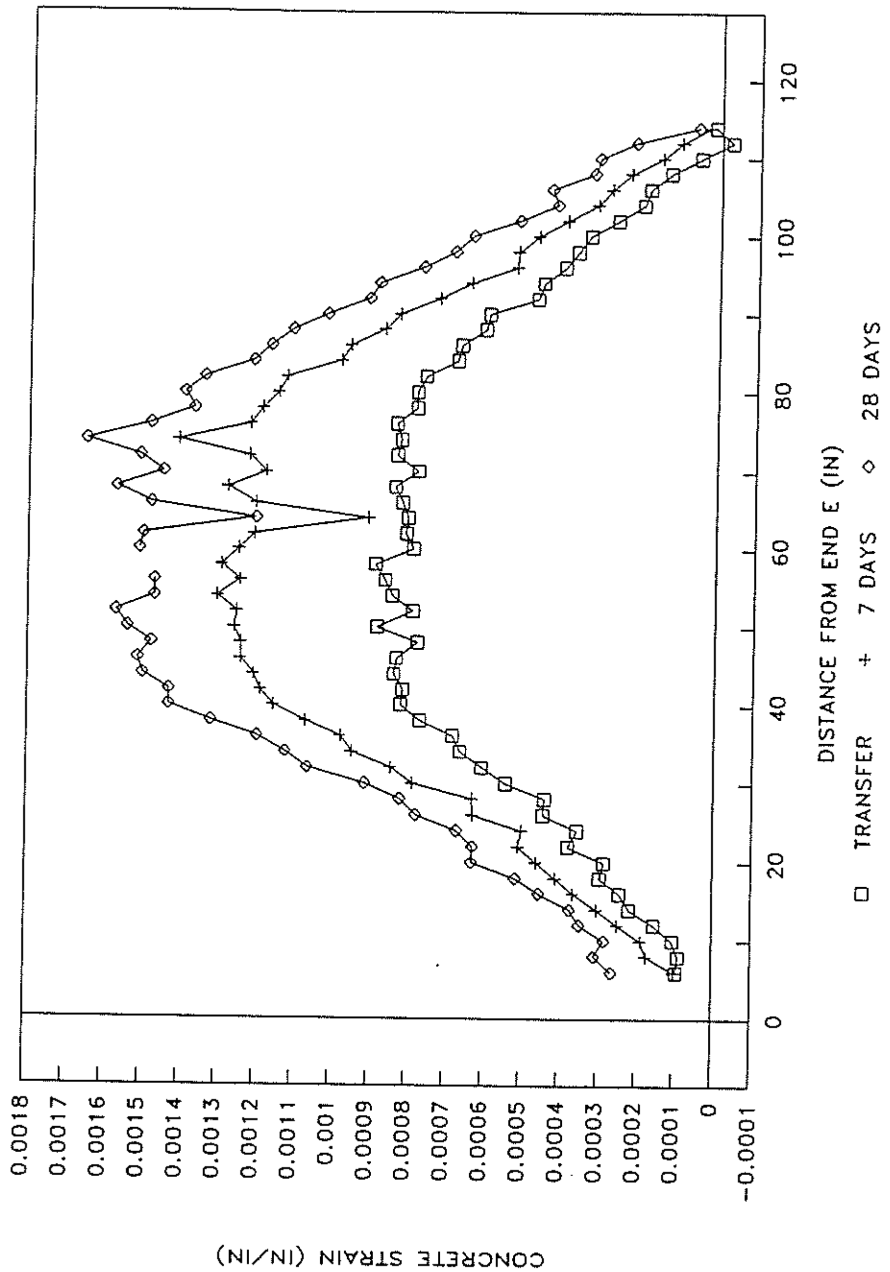
3U175AB2

CONCRETE STRAIN (IN/IN)
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C175CD2



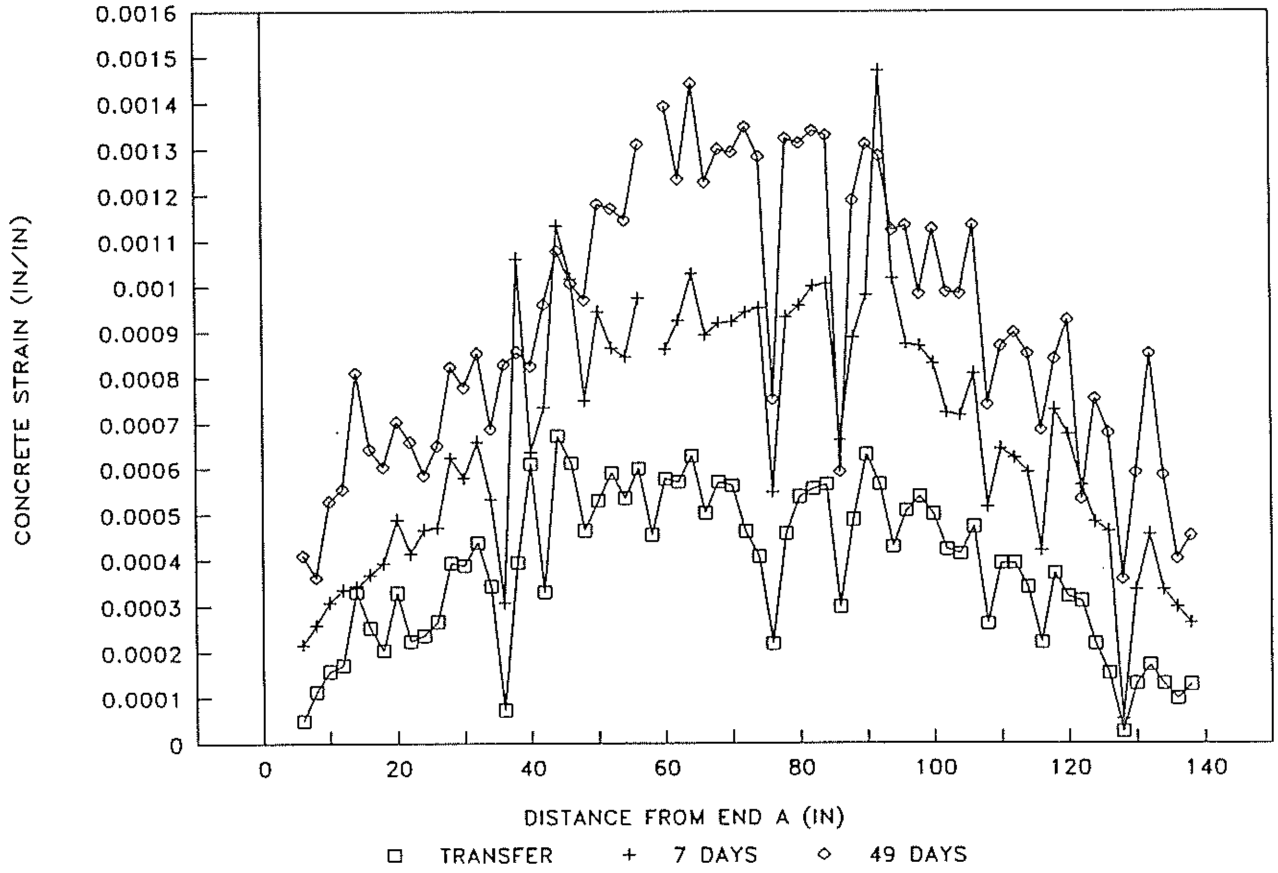
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS



3C175EF2

CONCRETE STRAIN (IN/IN)
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

U1625AB0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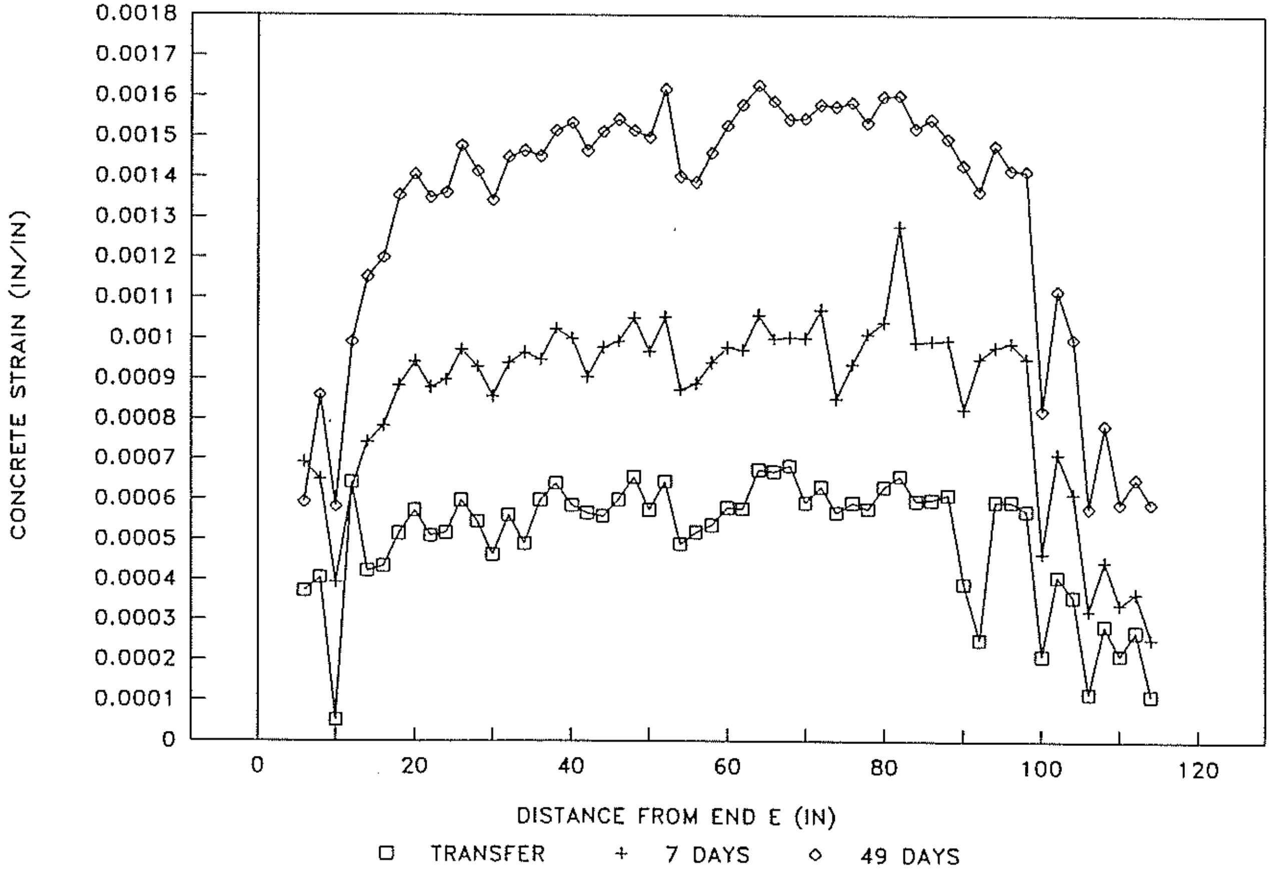
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 49 DAYS

C1625EFO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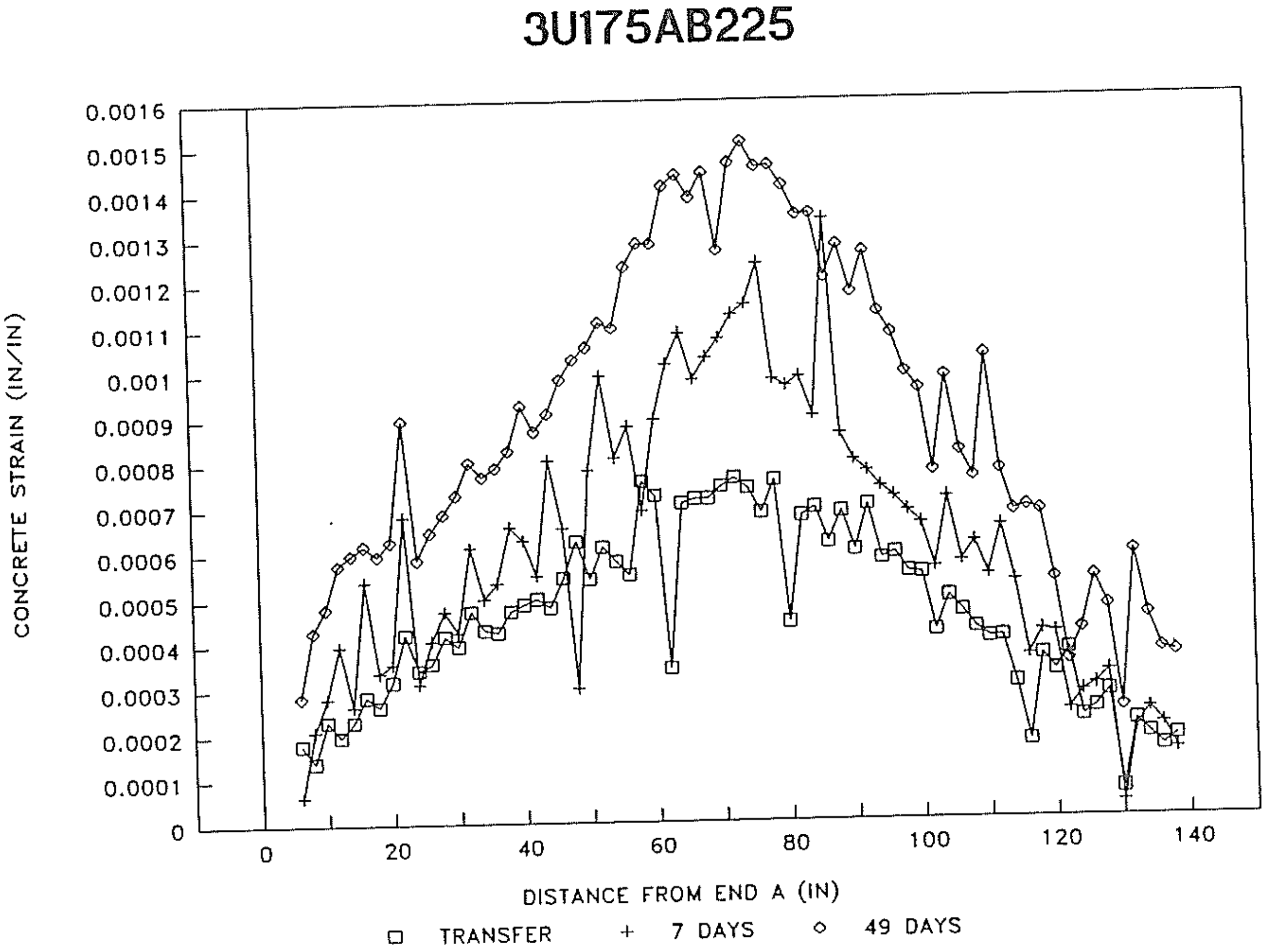
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 49 DAYS


3U175AB225
CONCRETE STRAIN (IN/IN)
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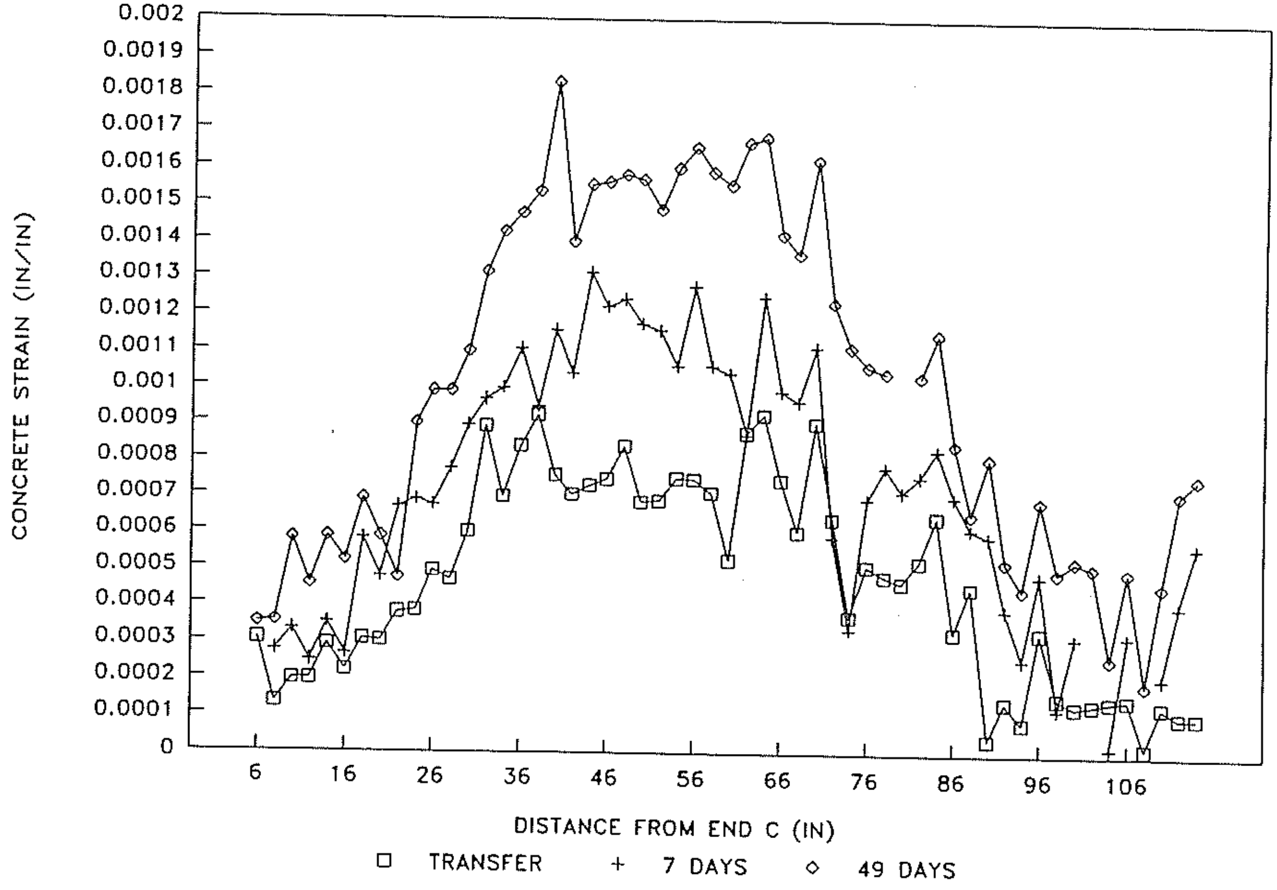
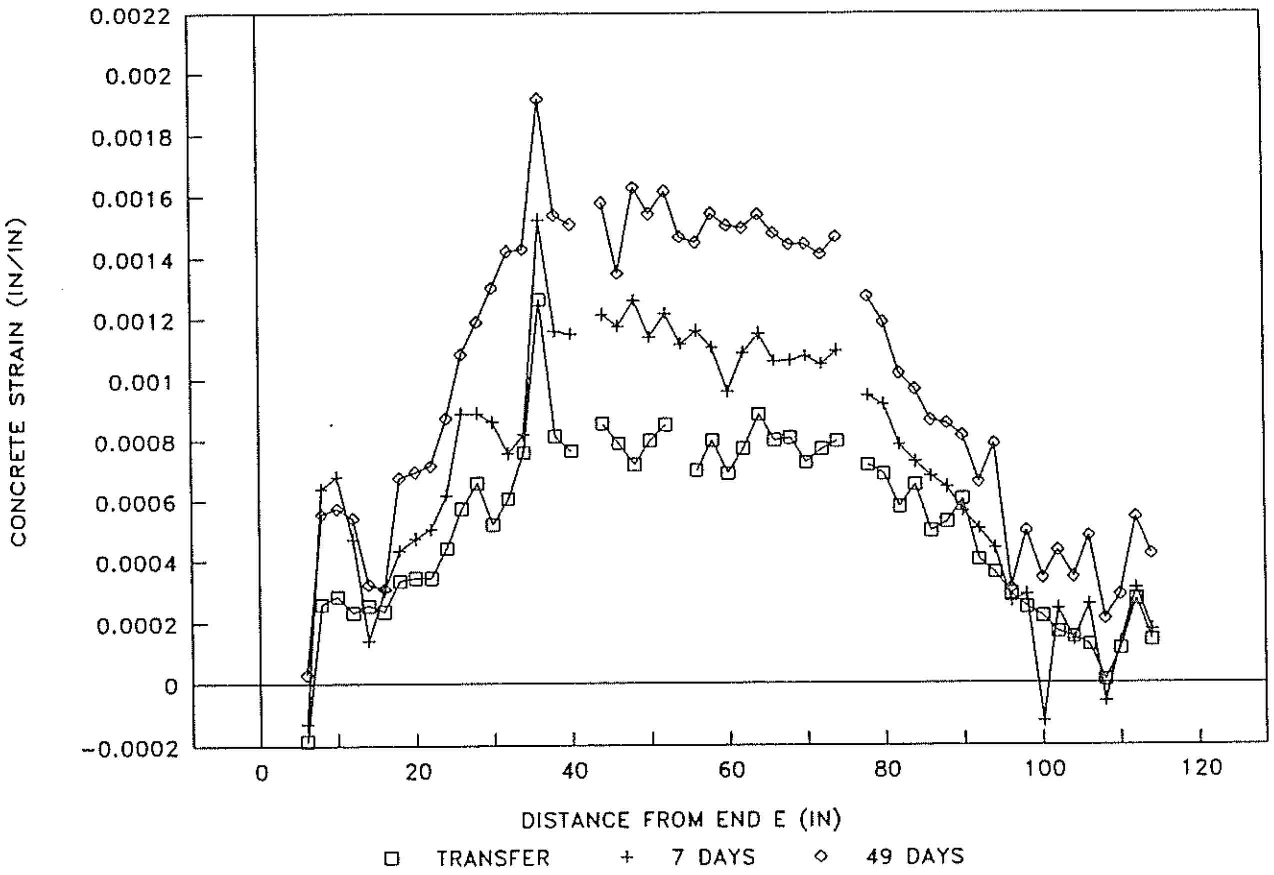
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER + 7 DAYS ◇ 49 DAYS

3C175CD225

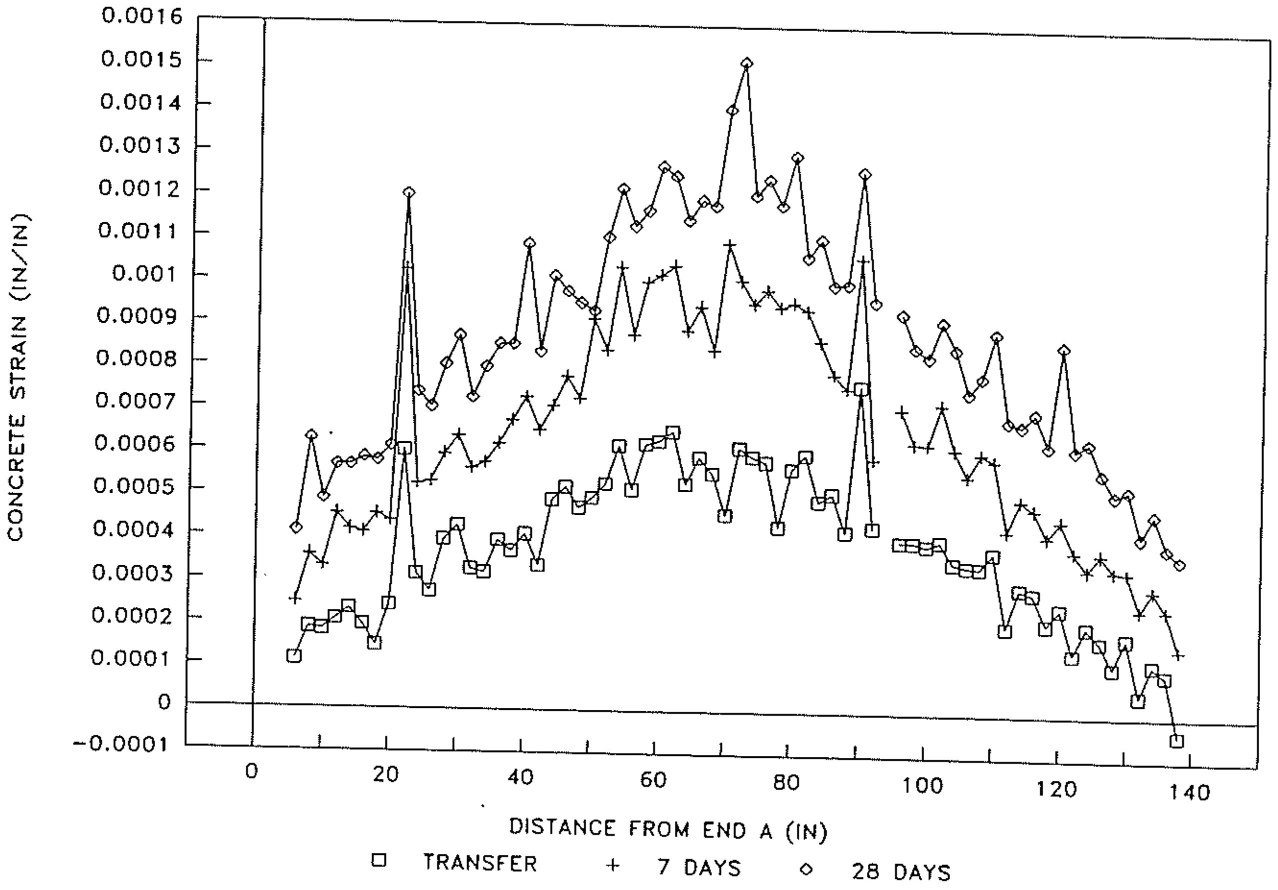

CONCRETE STRAIN (IN/IN)
0.002
0.0019
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
6
16
26
36
46
56
66
76
86
96
106
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 49 DAYS

3C175EF225



CONCRETE STRAIN (IN/IN)
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 49 DAYS

3U175AB25


CONCRETE STRAIN (IN/IN)
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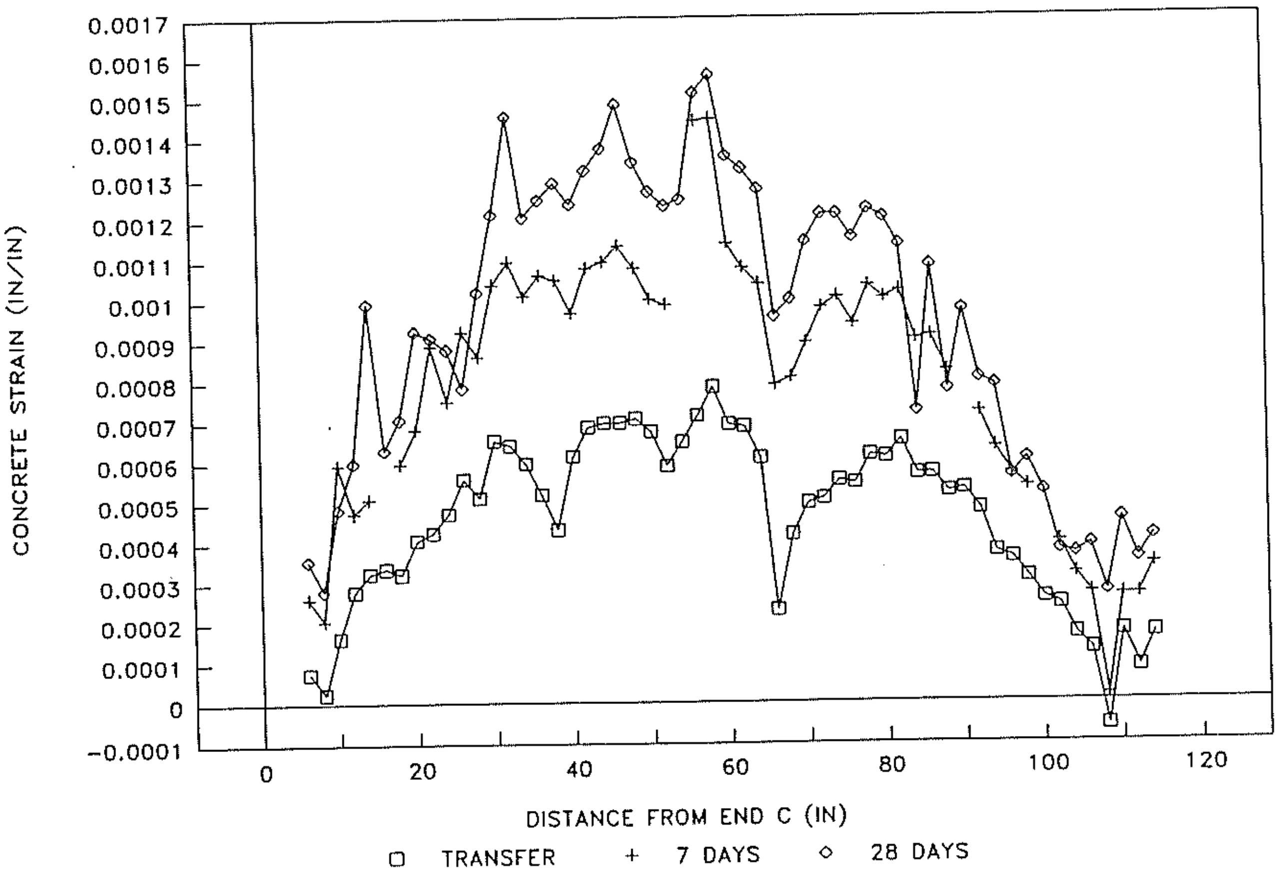
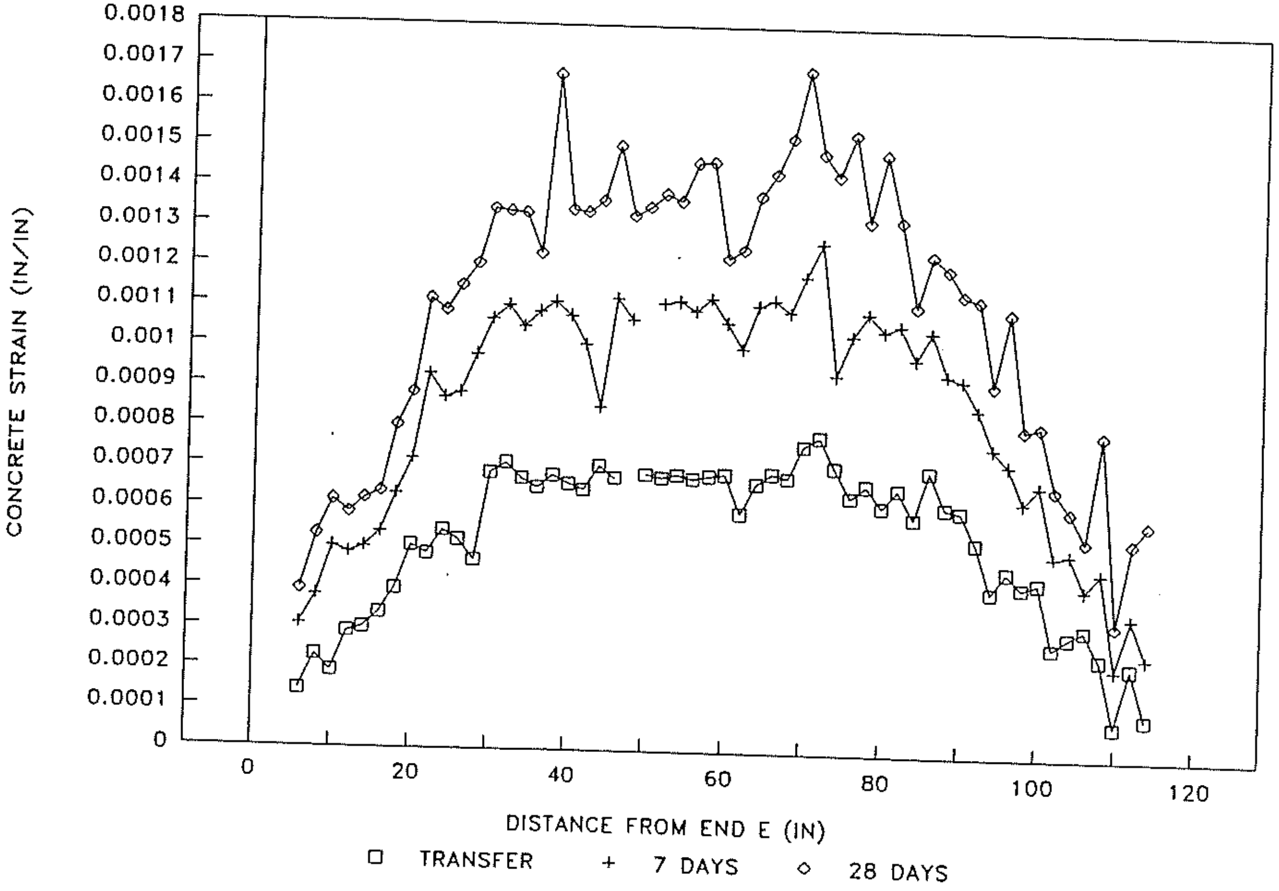
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

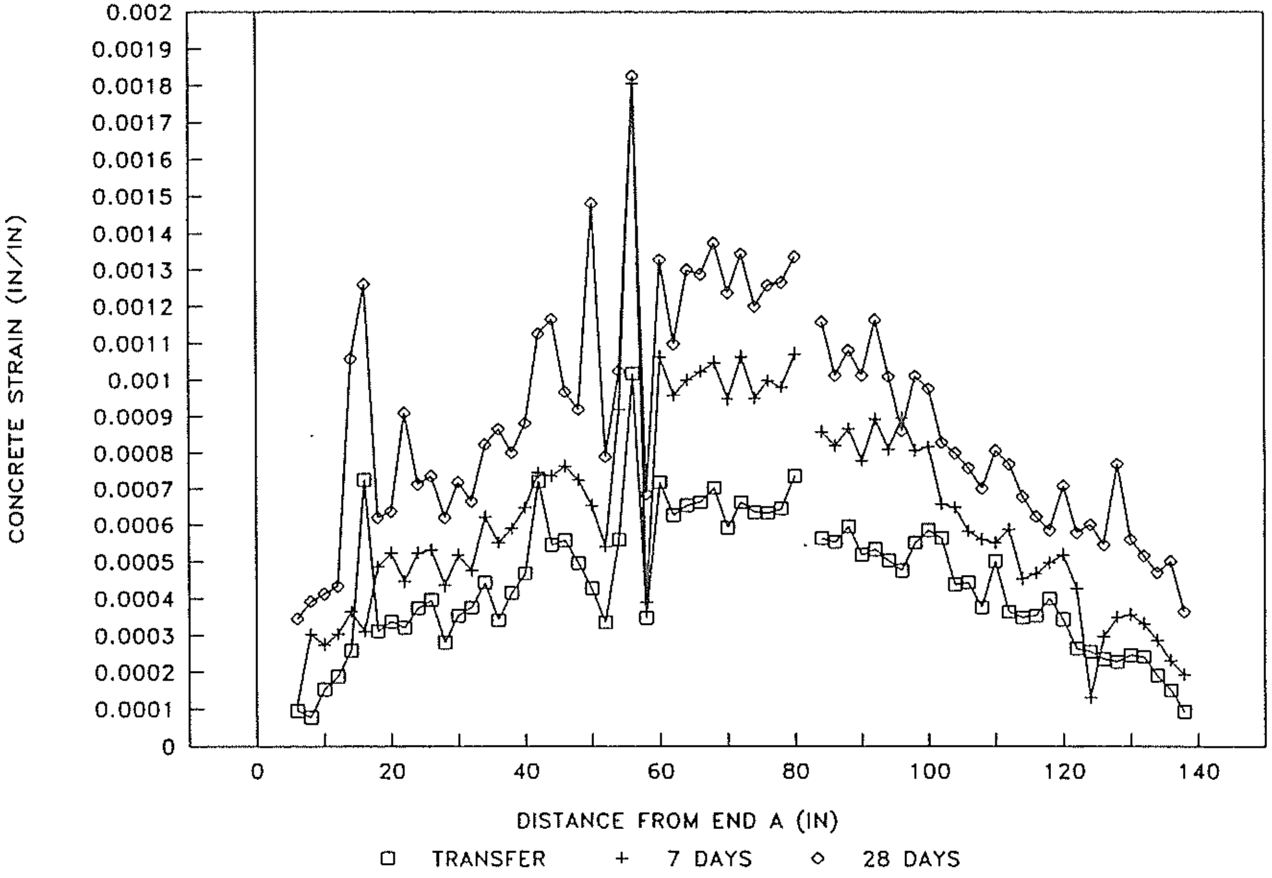
3C175CD25


CONCRETE STRAIN (IN/IN)
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

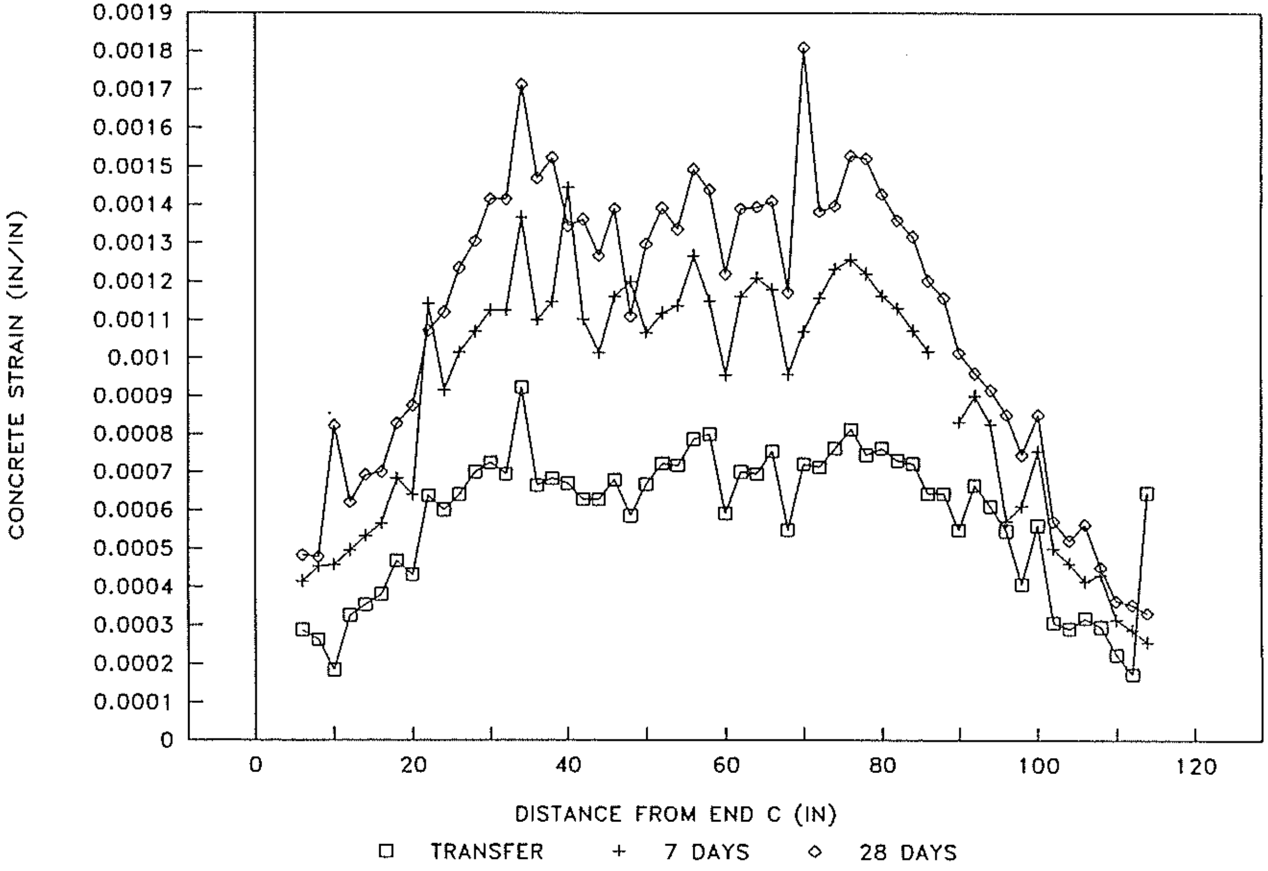
3C175EF25


CONCRETE STRAIN (IN/IN)
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

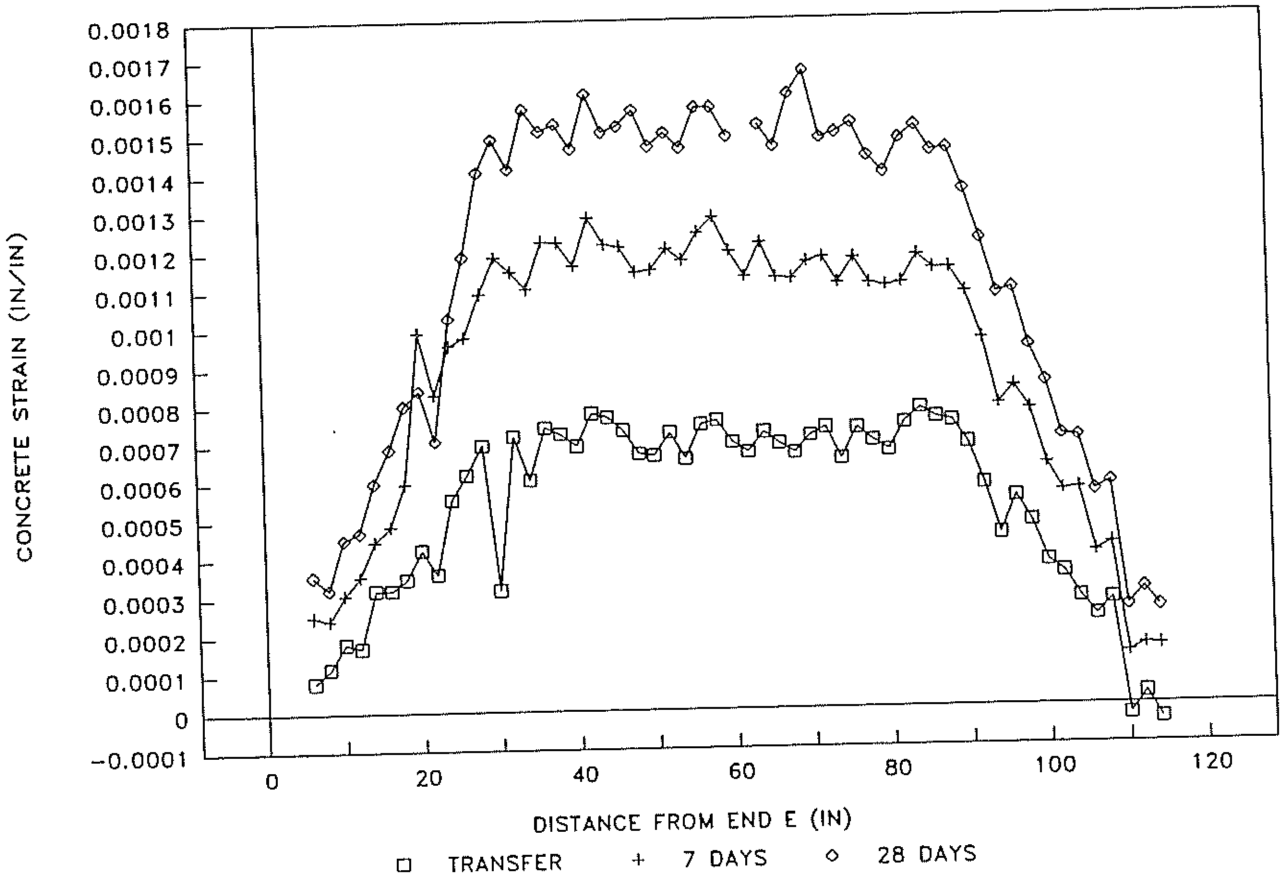
3U175AB225*


CONCRETE STRAIN (IN/IN)
0.002
0.0019
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C175CD225*


CONCRETE STRAIN (IN/IN)
0.0019
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C175EF225*



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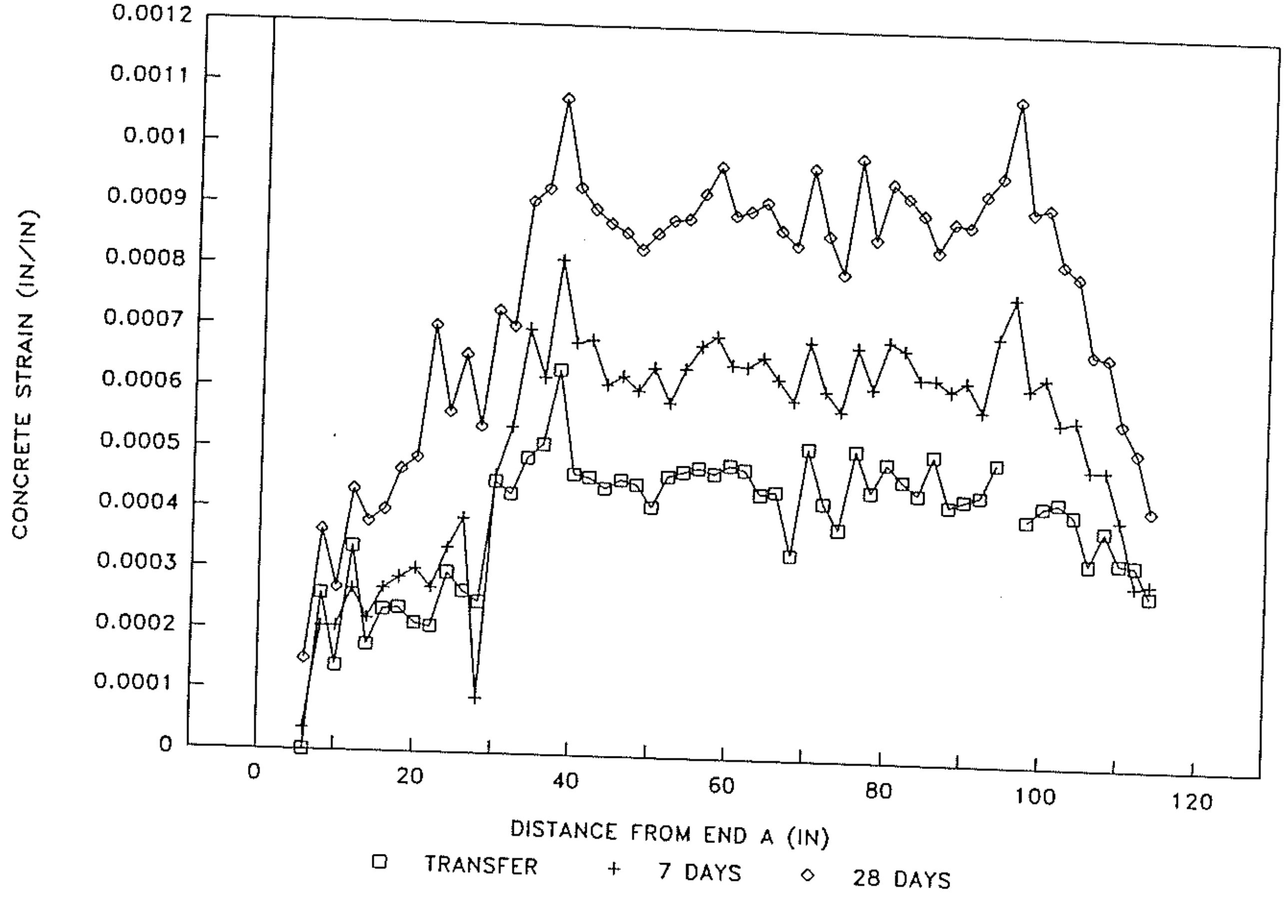
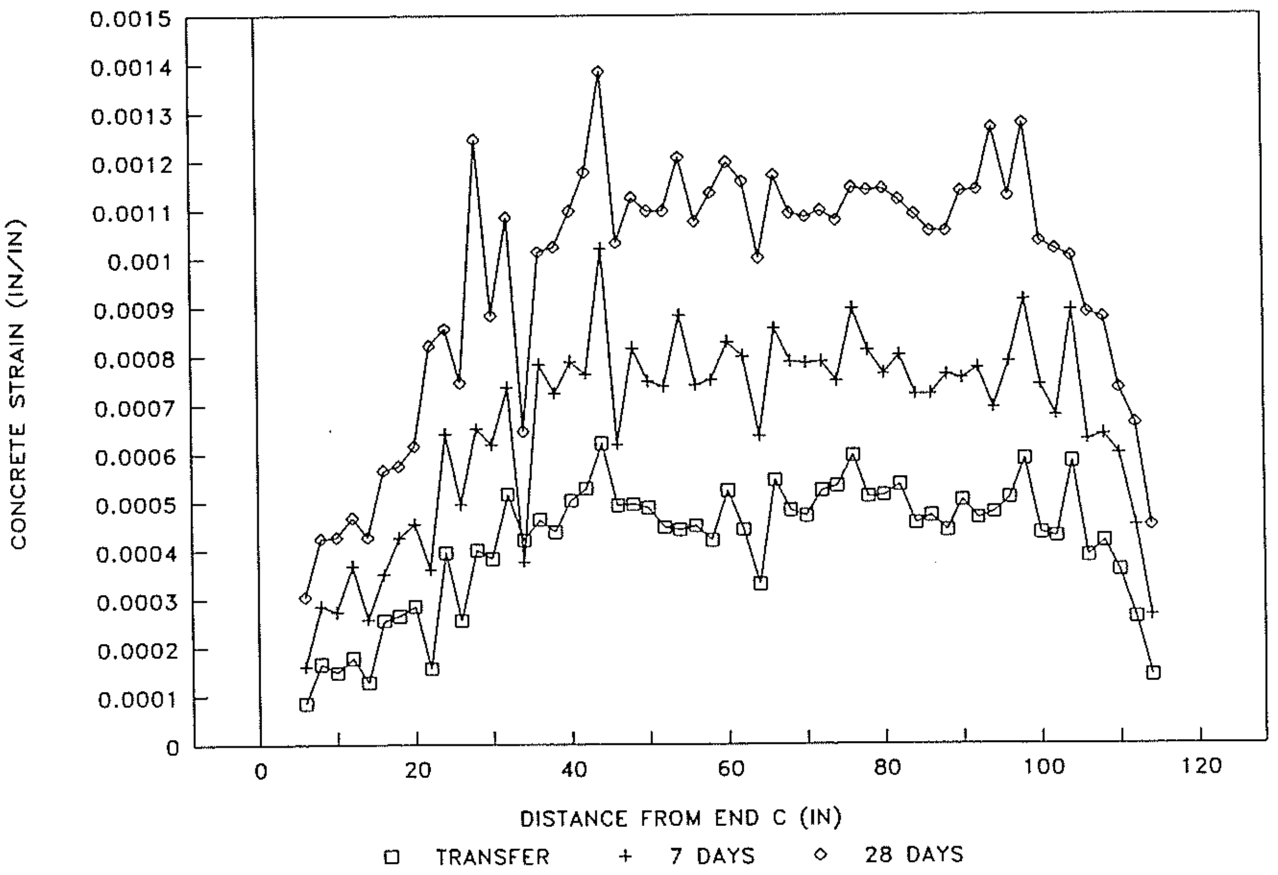
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

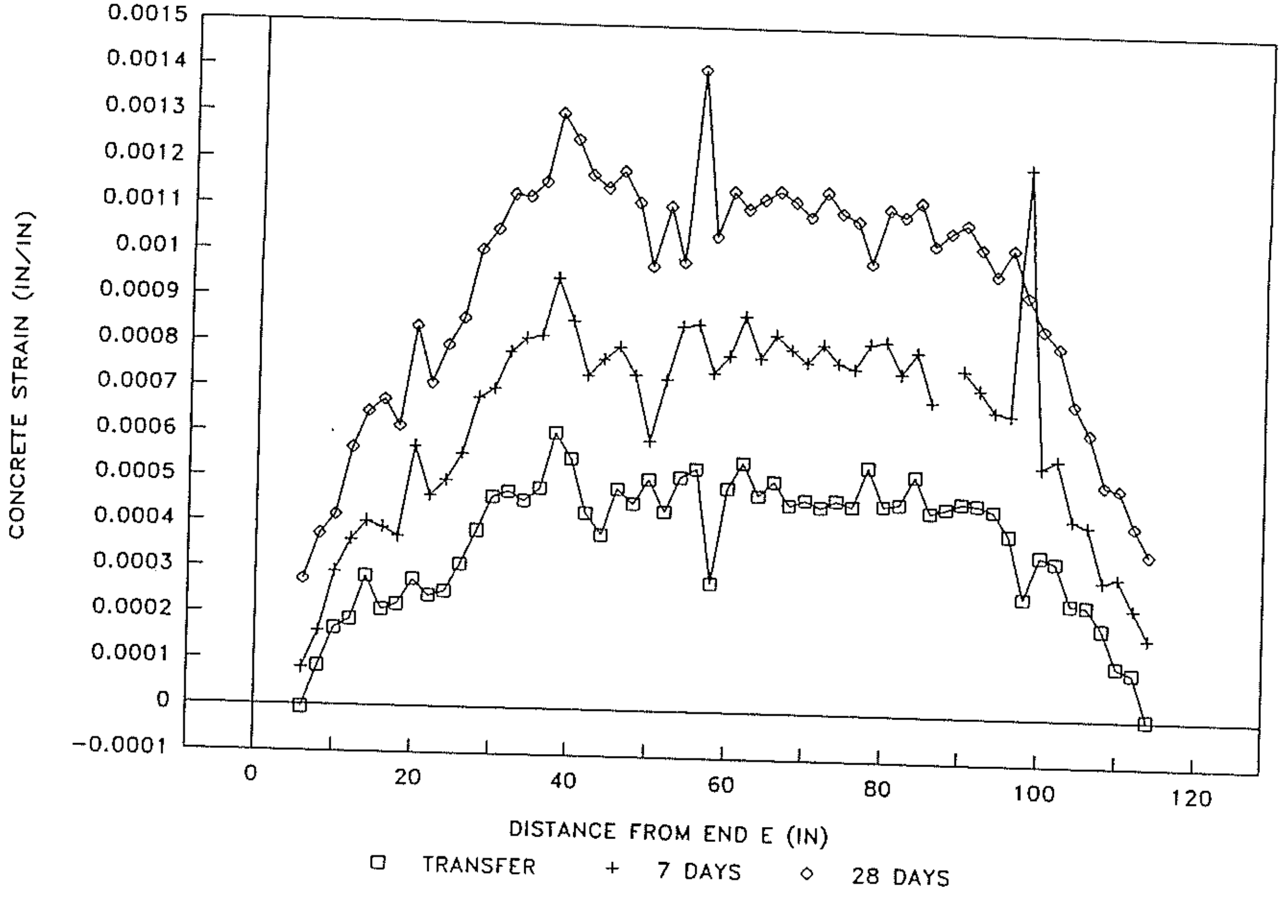
3C225AB275


0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C20CD275


CONCRETE STRAIN (IN/IN)
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C20EF275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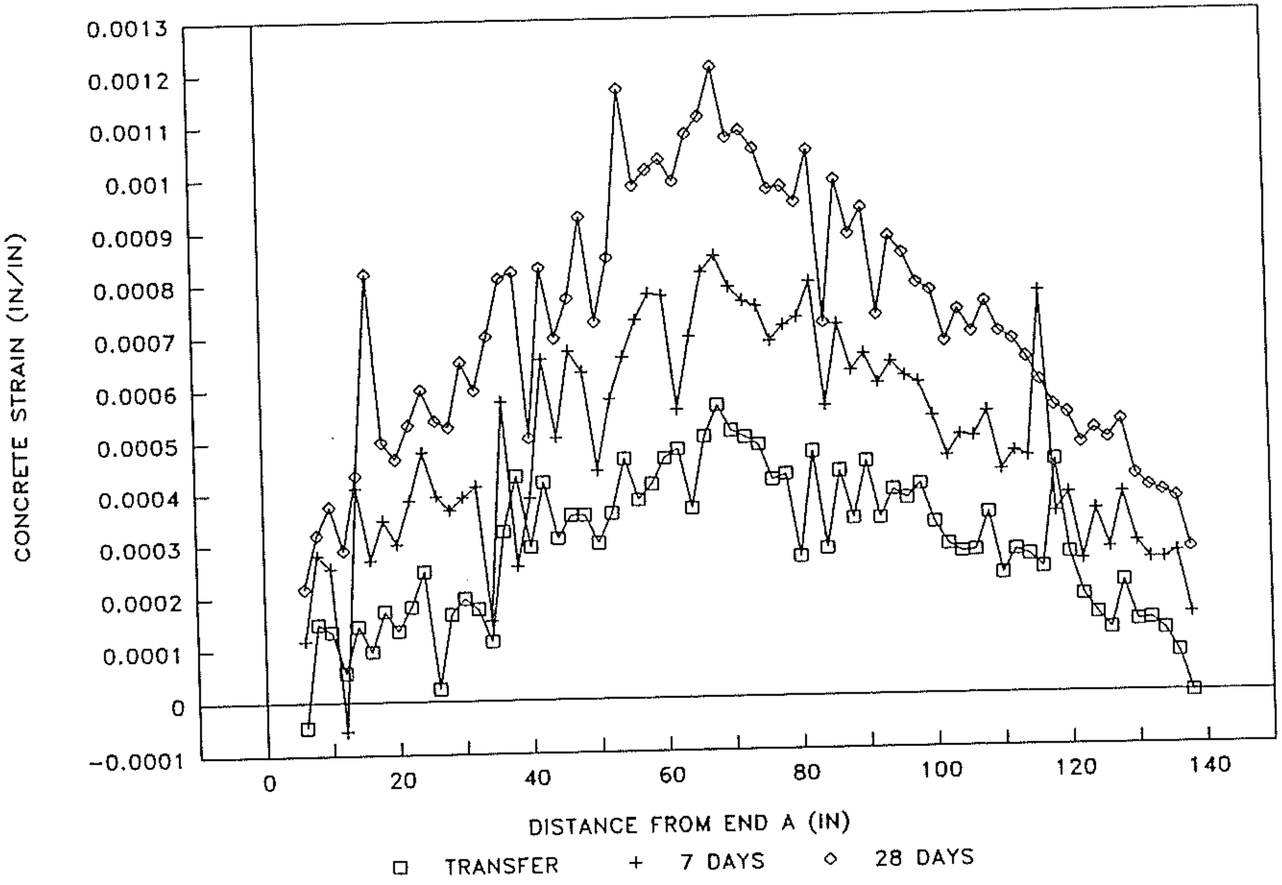
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
−0.0001
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3U20AB25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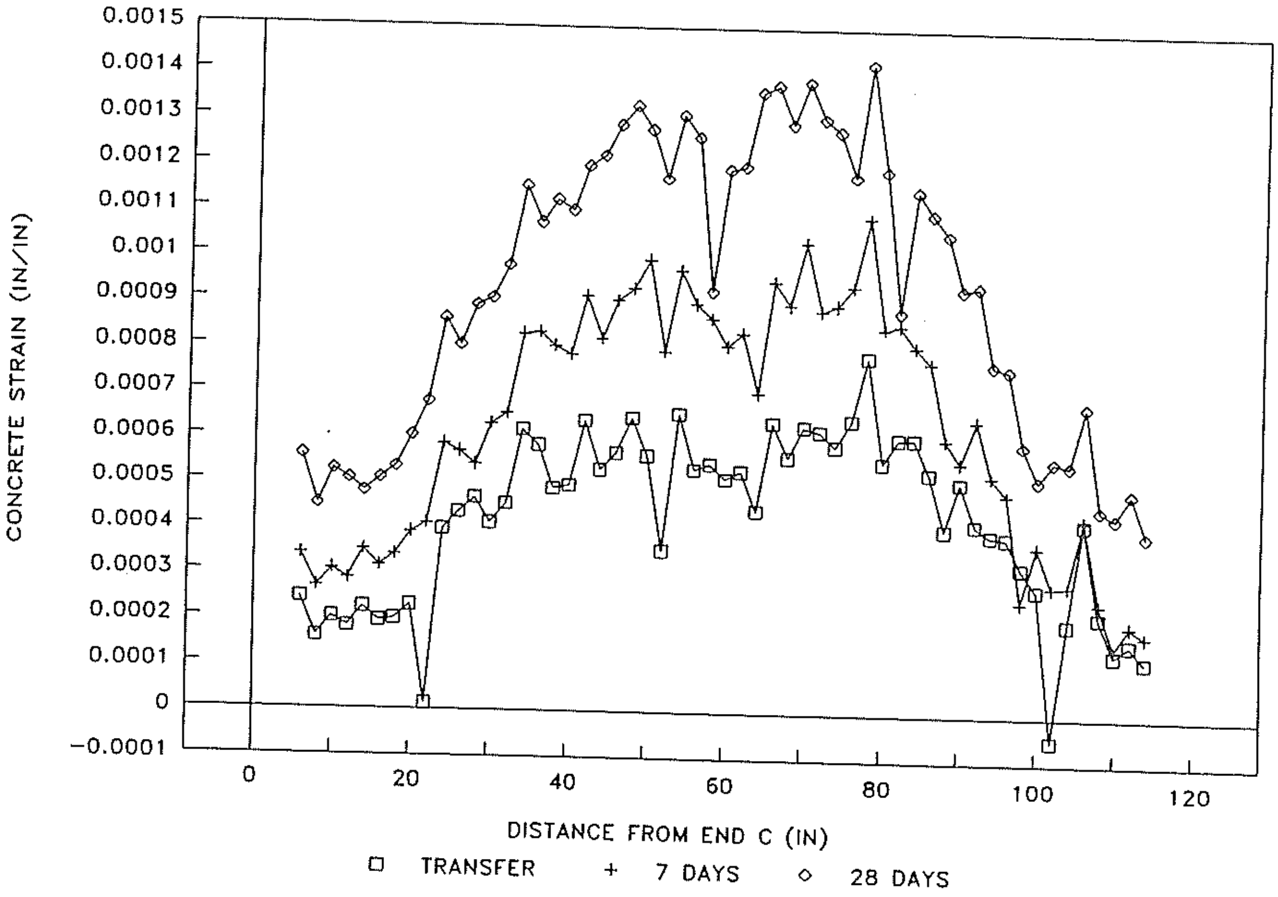
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C20CD25


CONCRETE STRAIN (IN/IN)
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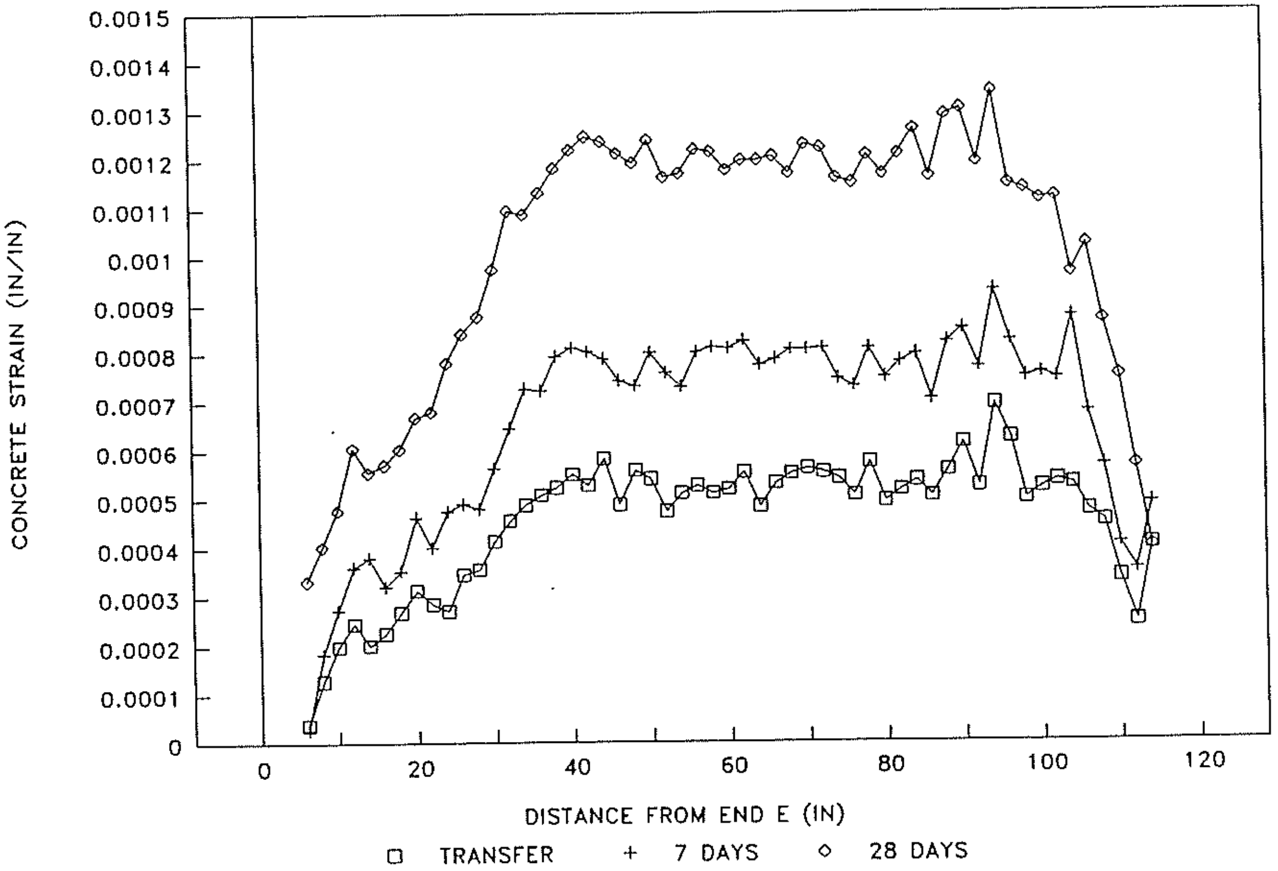
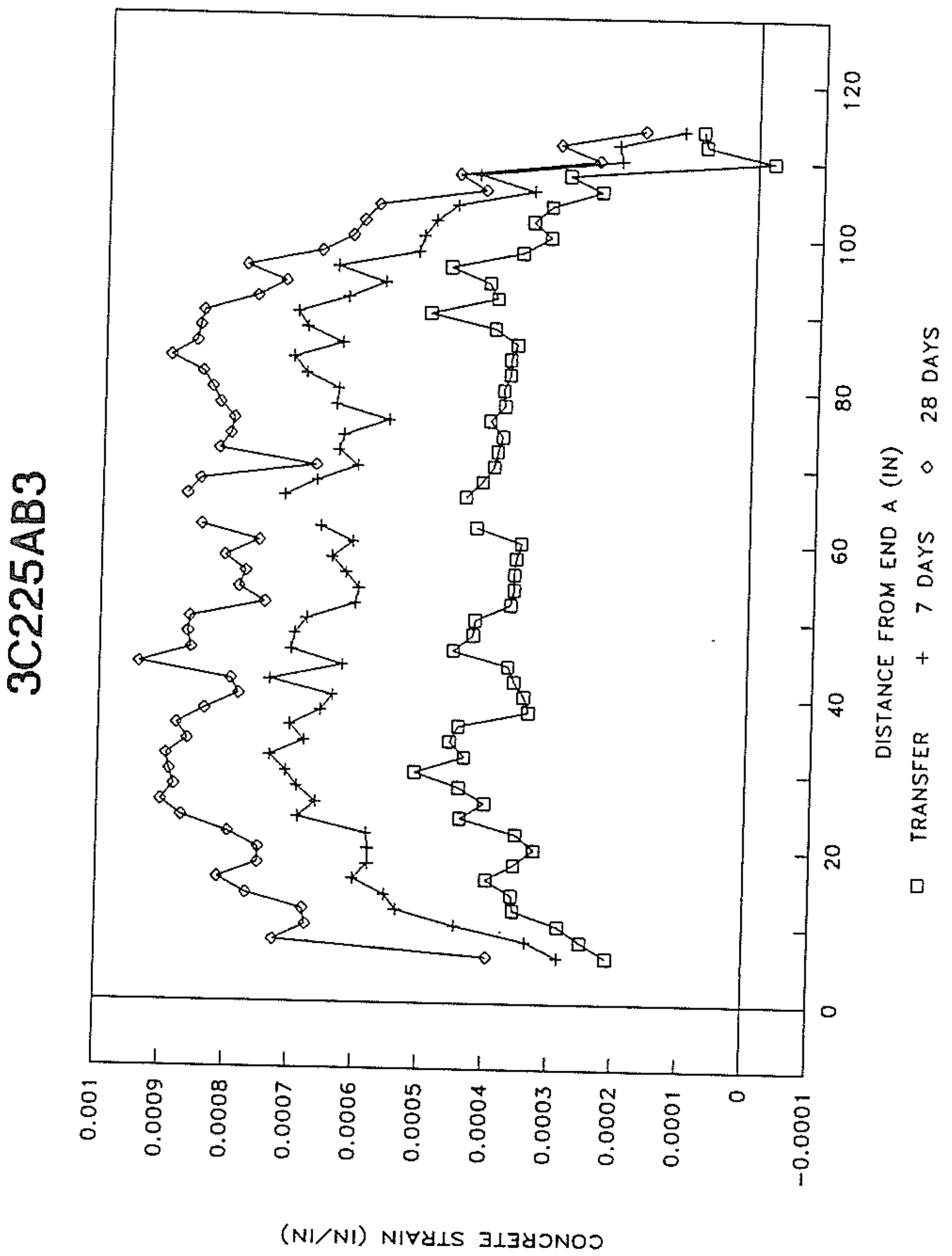
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
−0.0001
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS


3C20EF25

CONCRETE STRAIN (IN/IN)
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS



3C225AB3

CONCRETE STRAIN (IN/IN)
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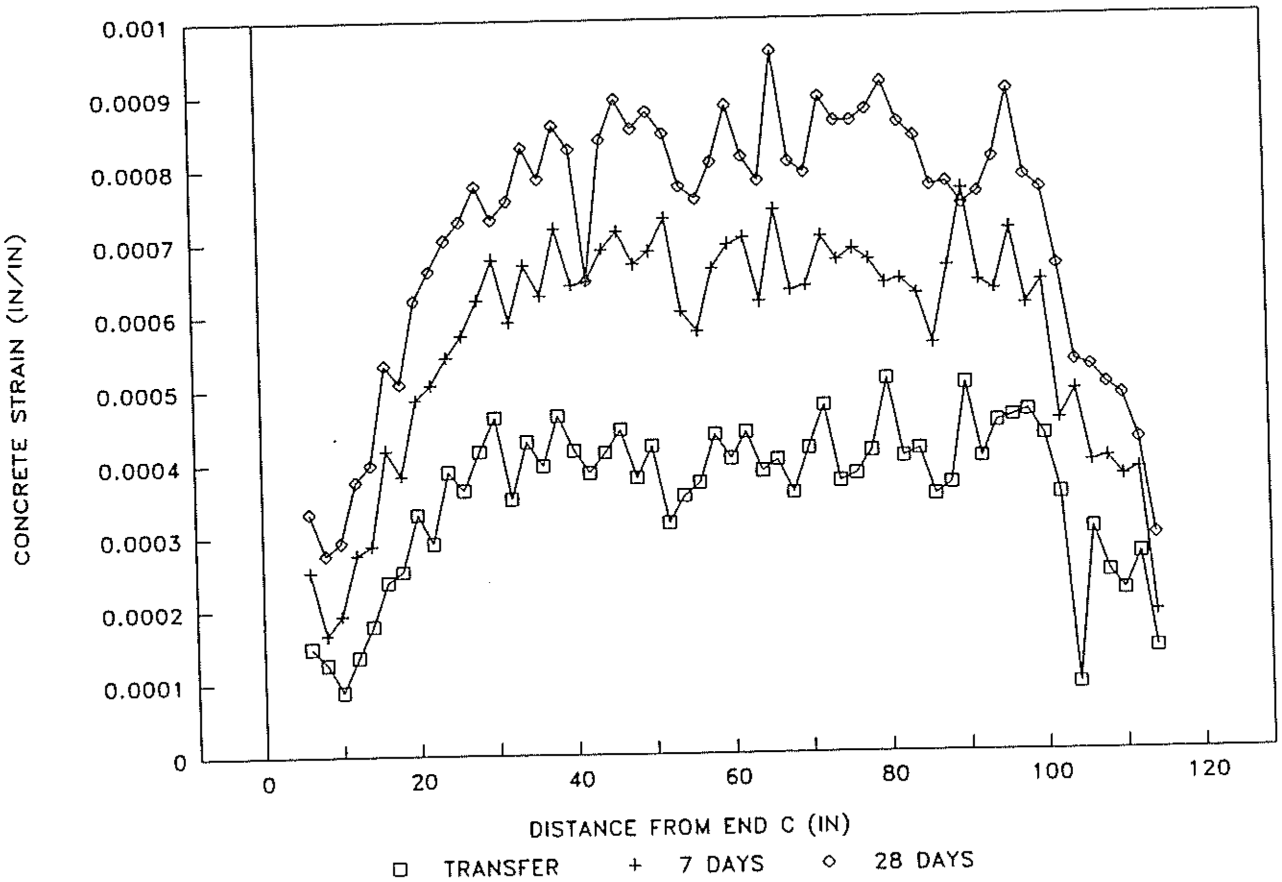
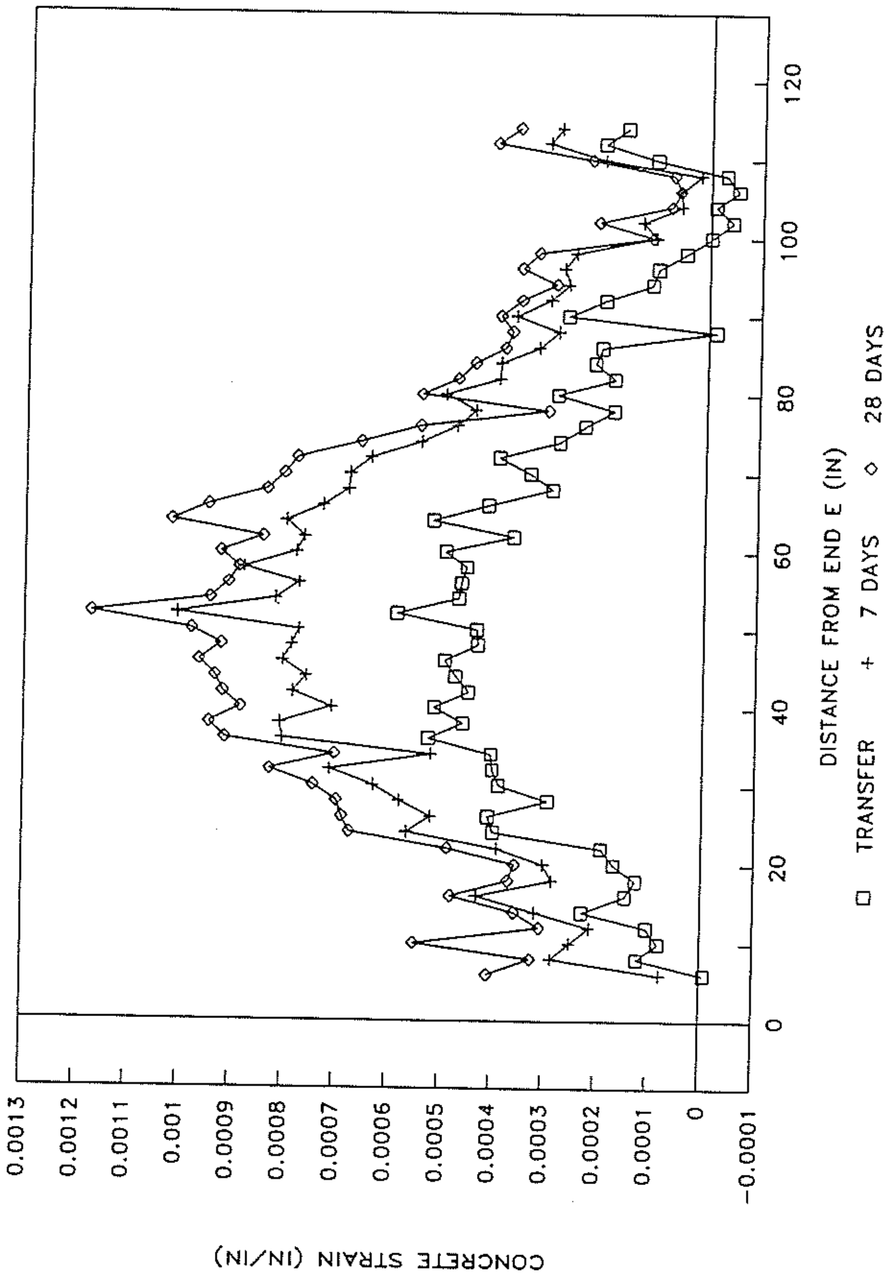
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
0
20
40
60
80
100
120
DISTANCE FROM END A (IN)
□ TRANSFER + 7 DAYS ◇ 28 DAYS

3C225CD3


0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

3C20EF3


CONCRETE STRAIN (IN/IN)
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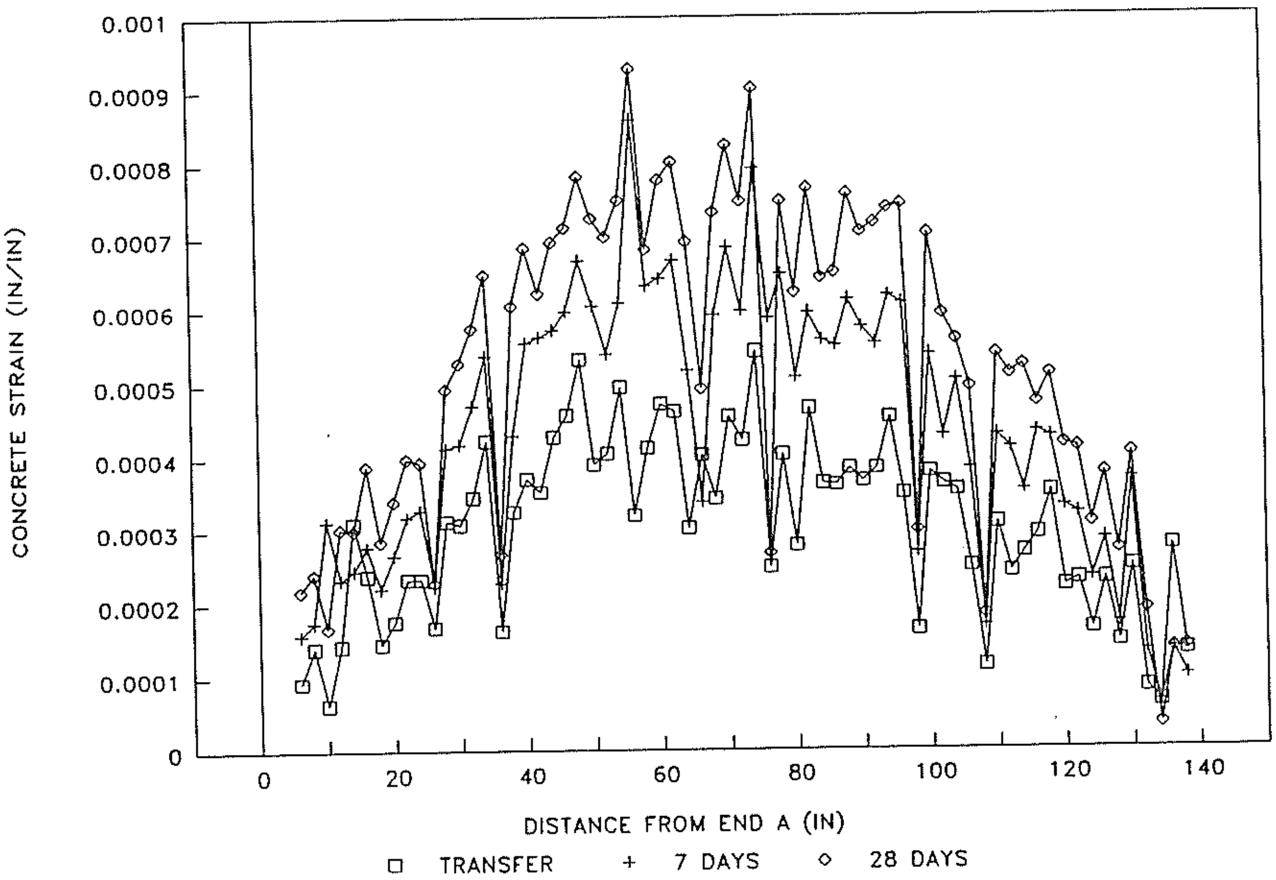
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER + 7 DAYS ◇ 28 DAYS

6U225AB3


CONCRETE STRAIN (IN/IN)
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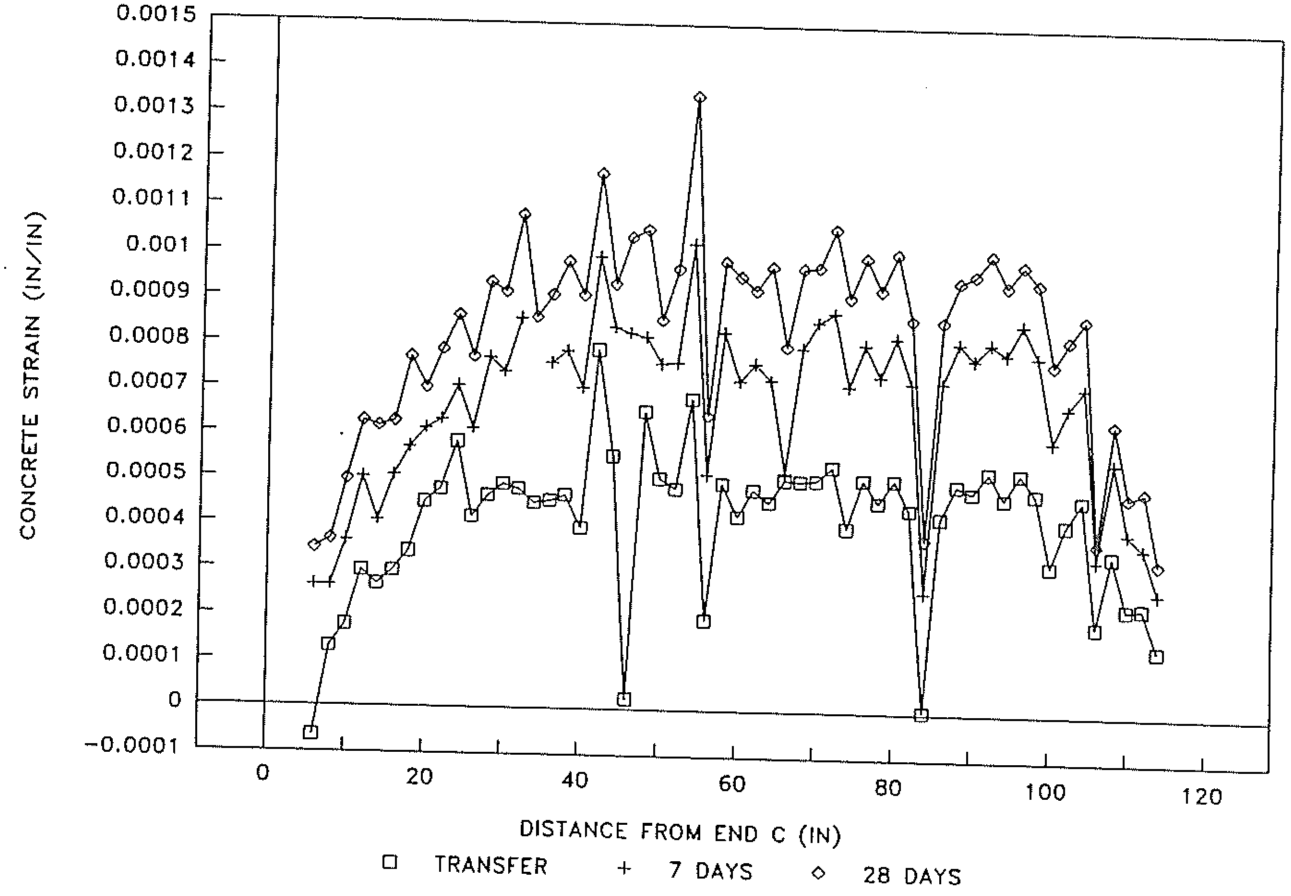
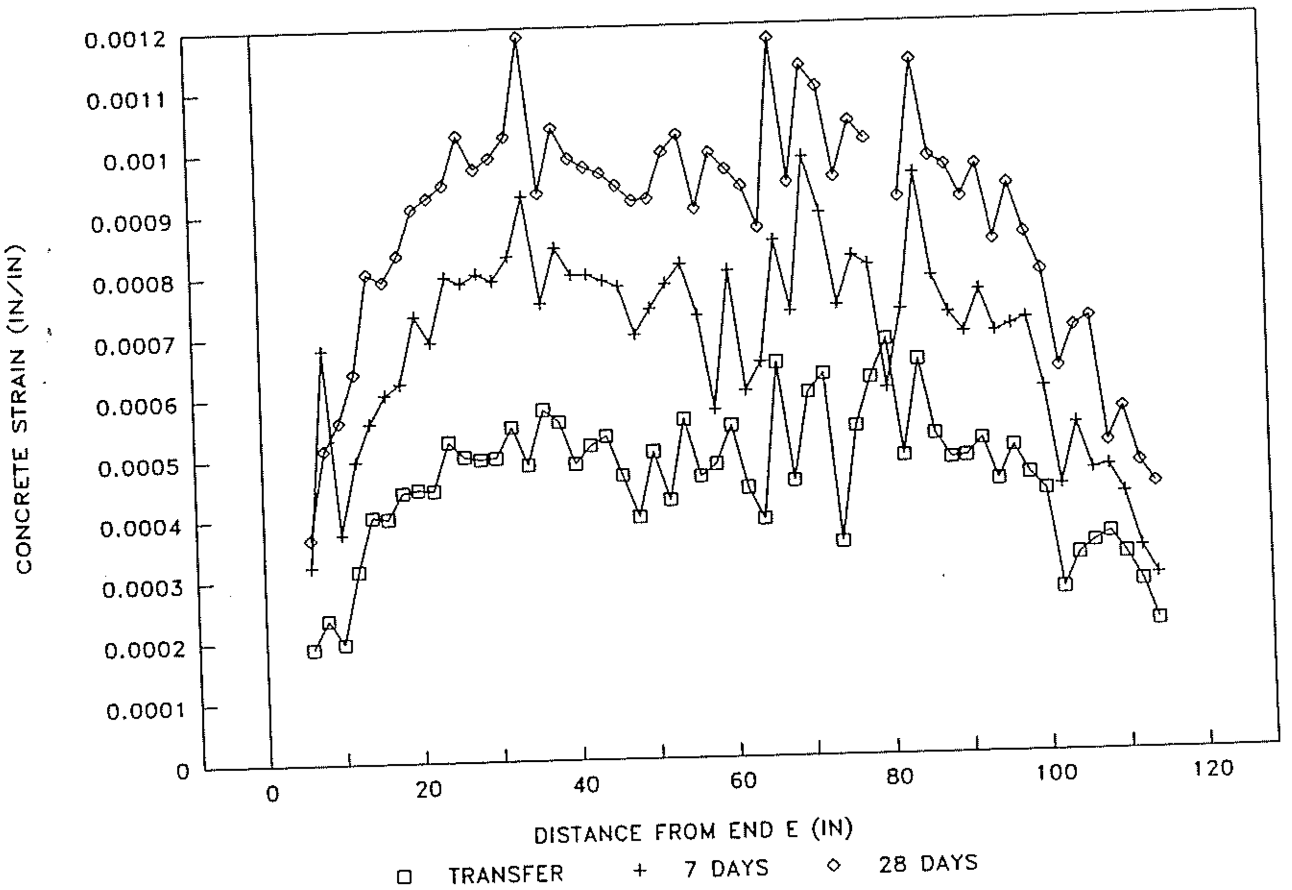
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

6C225CD3



0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
CONCRETE STRAIN (IN/IN)
0
20
40
60
80
100
120
DISTANCE FROM END C (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

6C225EF3


CONCRETE STRAIN (IN/IN)
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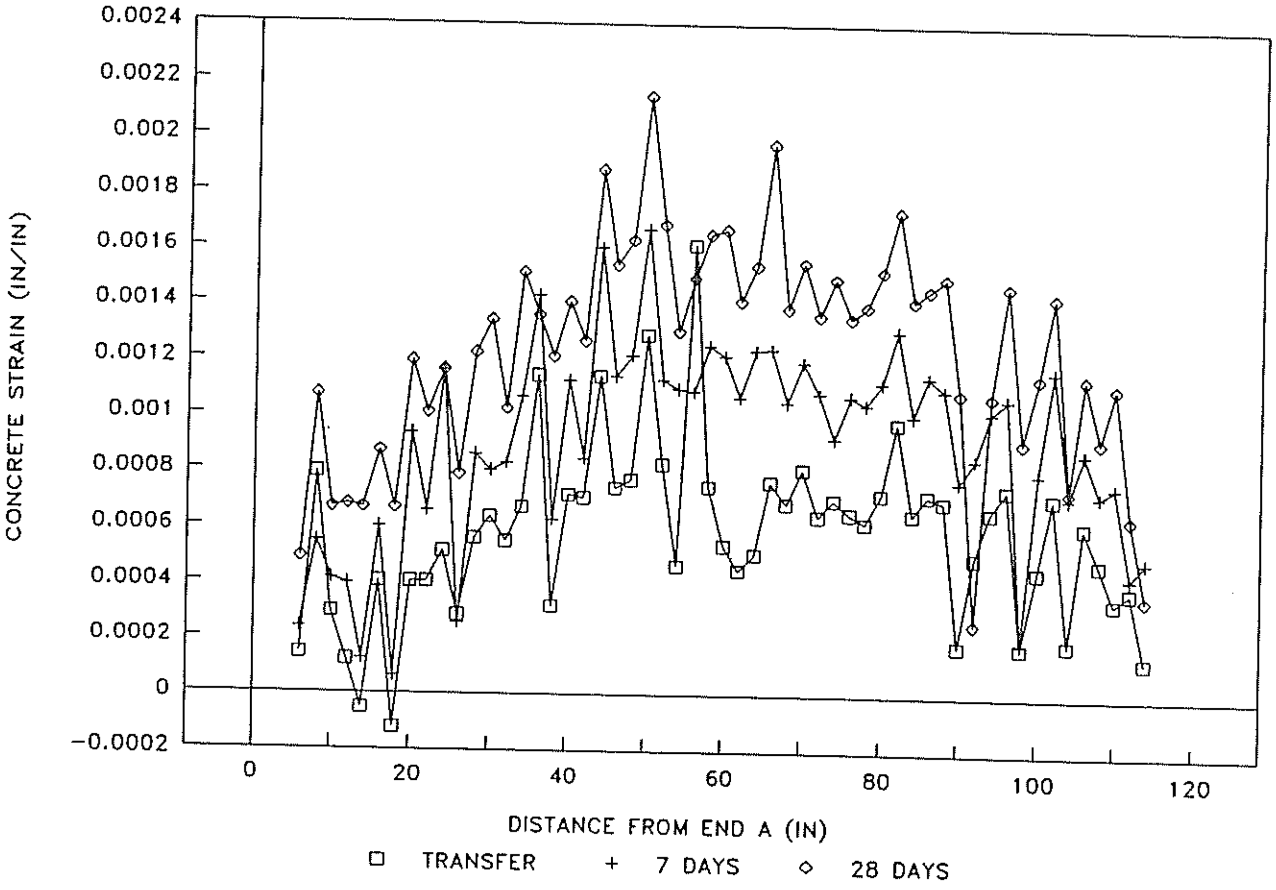
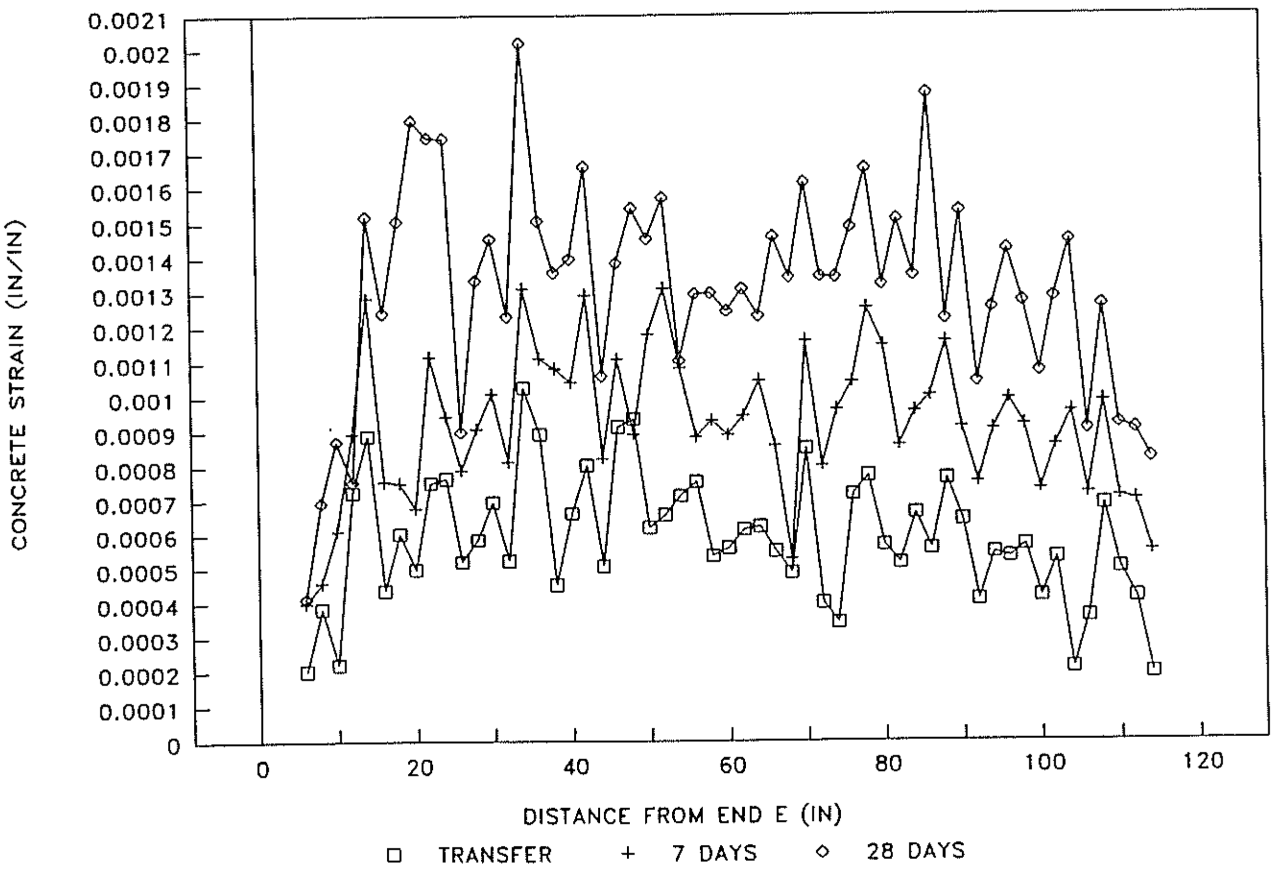
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

6C20AB275


CONCRETE STRAIN (IN/IN)
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
−0.0002
0
20
40
60
80
100
120
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

6C225EF275


CONCRETE STRAIN (IN/IN)
0.0021
0.002
0.0019
0.0018
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
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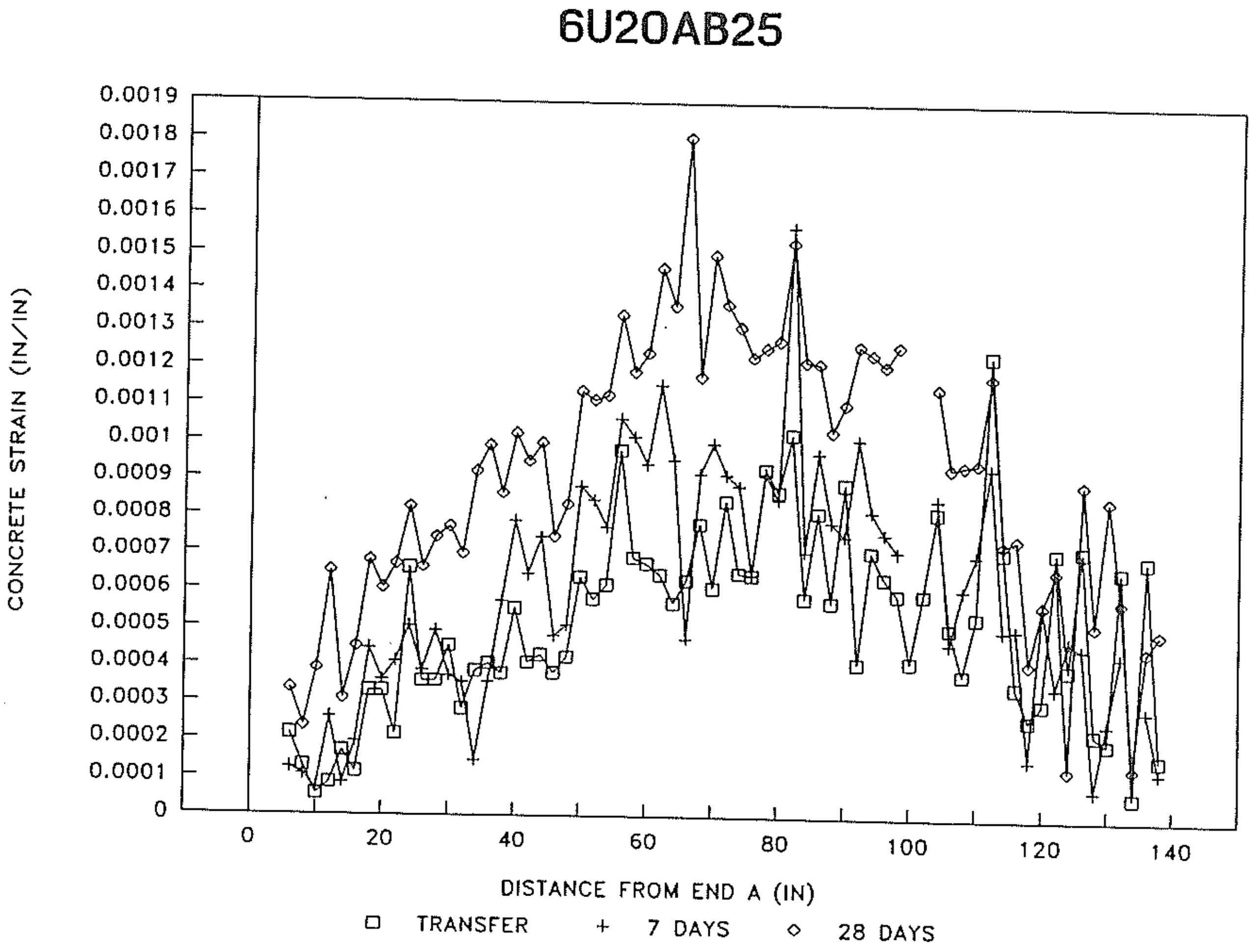
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS


6U20AB25
CONCRETE STRAIN (IN/IN)
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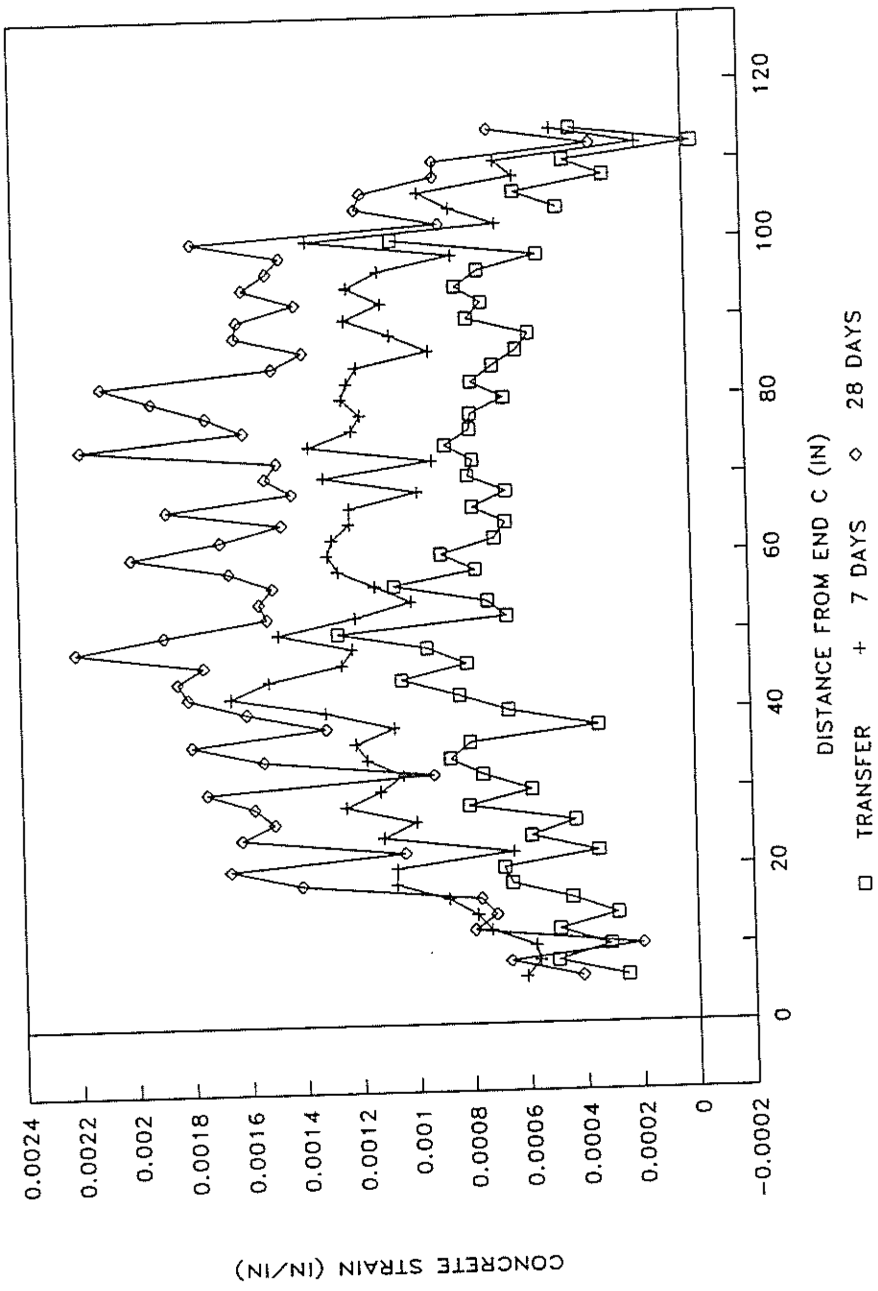
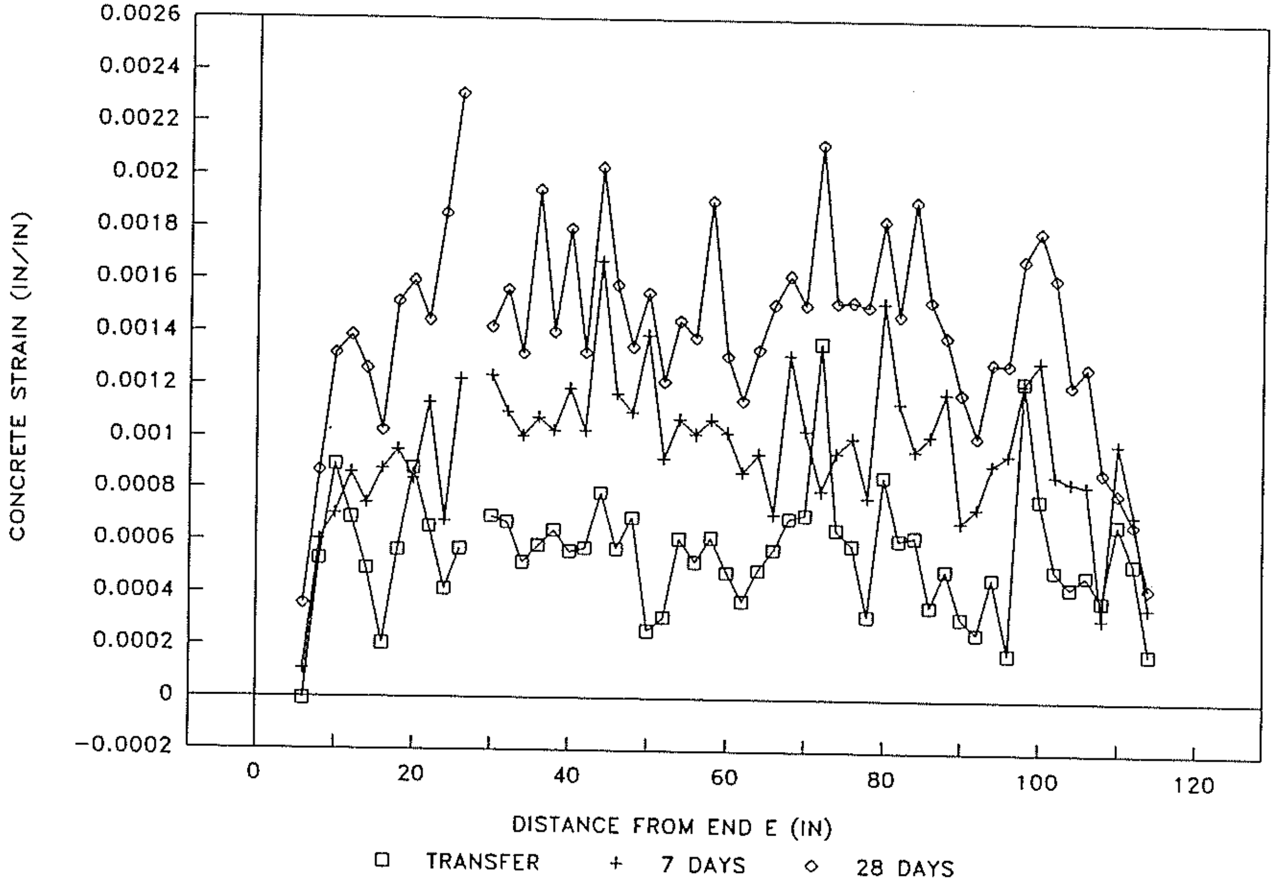
0.0017
0.0016
0.0015
0.0014
0.0013
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
DISTANCE FROM END A (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

6C20CD25


CONCRETE STRAIN (IN/IN)
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
DISTANCE FROM END C (IN)
0
20
40
60
80
100
120
□ TRANSFER + 7 DAYS ◇ 28 DAYS

6C225EF25


CONCRETE STRAIN (IN/IN)
0.0026
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
−0.0002
0
20
40
60
80
100
120
DISTANCE FROM END E (IN)
□ TRANSFER
+ 7 DAYS
◇ 28 DAYS

APPENDIX C

TABLES OF TRANSFER LENGTHS AND AVERAGE END SLIPS

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
U15AB0	A	–	–	–	.21025	–	–	–	–	–
	B^{cr}	–	–	–	–	–	–			
U15CD0	C^{cr}	–	–	–	–	–	–	–	–	–
	D	–	–	–	–	–	–			
C15EF0	E^{cr}	–	–	–	–	–	–	–	–	–
	F^{cr}	–	–	–	.25735	–	–			
C15GH0	G^{cr}	–	–	–	.28065	–	–	–	–	–
	H^{cr}	–	–	–	.20385	–	–			
U175AB0	A	58	58	58	.22744	.22449	.63159	6.0	9.0	12.0
	B	76	76	76	.29134	.27594	.68829			
C175CD0	C	18	19	32	–	–	–	5.4	8.8	11.8
	D	22	24	28	.06314	.70504	.48314			
C175EF0	E	24	27	27	.06099	.06789	.47624	6.0	10.1	12.8
	F	24	28	29	.12494	.13119	.54254			

TR= Transfer, 7D= 7 Days, 28D= 28 Days, ^{cr}=Denotes Cracked End, ^{L}=49 Days
– = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens U15AB0, U15CD0, C15EF0, C15GH0, U175AB0, C175CD0, and C175EF0,

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
3C175CD225	C^{cr}	33	37	40^{t}	.14592	-	$.15062^{t}$	7.8	11.4	15.9
	D^{cr}	62	65	66^{t}	.20202	-	$.20792^{t}$			
3C175EF225	E^{cr}	34	34	34^{t}	.15051	-	$.15721^{t}$	7.7	11.5	15.4
	F^{cr}	53	53	53^{t}	.19472	-	$.20659^{t}$			
3U175AB25	A	54	56	62	.19299	.19078	.19488	5.7	9.3	12.3
	B	62	64	67	.22511	.22366	.22206			
3C175CD25	C^{cr}	28	30	31	.09834	.10428	.10201	6.0	10.6	13.4
	D^{cr}	37	42	55	.15506	.16463	.16304			
3C175EF25	E^{cr}	30	32	40	.11993	.13284	.12396	6.8	10.9	14.2
	F^{cr}	34	44	47	.12664	.13138	.12526			
3U175AB225*	A	55	57	60	.22342	.22857	.23556	6.4	9.8	12.3
	B	62	64	66	.23052	.23893	.22632			
3C175CD225*	C^{cr}	29	32	33	.15331	.14889	.14514	4.2	11.3	13.9
	D^{cr}	40	44	45	.14274	.15746	.14684			

TR= Transfer, 7D= 7 Days, 28D= 28 Days, ^{cr}=Denotes Cracked End, ^{t}=49 Days
- = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens 3C175CD225, 3C175EF225, U175AB25, 3C175CD25, 3C175EF25, 3U175AB225*, and 3C175CD225*, 3C20CD275

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
3C175EF225*	E^{cr}	27	30	31	.09922	.10534	.10169	7.1	11.3	14.5
	F^{cr}	32	35	38	.11742	.13259	.12907			
3C225AB275	A^{cr}	34	35	37	.12071	.12402	.12084	4.6	6.2	9.3
	B	26	24	24	.06301	.07711	.07119			
3C20CD275	C^{cr}	39	41	41	.12401	.12866	.12392	4.8	7.4	11.2
	D	24	24	24	.05384	.06421	.06482			
3C20EF275	E^{cr}	30	33	33	.14526	.13849	.11041	4.6	7.3	11.0
	F^{cr}	28	36	37	.07581	.08507	.08607			
3U20AB25	A	60	60	64	.23855	.24525	.24139	4.6	7.4	10.5
	B	72	72	72	-	-	-			
3C20CD25	C^{cr}	45	46	47	-	-	-	6.0	8.7	12.8
	D^{cr}	28	43	48	.19370	.20995	.19342			
3C20EF25	E^{cr}	37	38	38	.16335	.16574	.13505	5.3	7.7	11.8
	F	18	18	25	.04190	.04692	.03394			

TR= Transfer, 7D= 7 Days, 28D= 28 Days, ^{cr}=Denotes Cracked End, ^{L}=49 Days
- = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens 3C175EF225*, 3C225AB275, 3C20CD275, 3C20EF275,3U20AB25, 3C20CD25,and 3C20EF25

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
3C225AB3	A	24	24	24	.03820	.05110	.04187	4.2	6.8	8.4
	B	27	30	30	.10809	.10760	.10562			
3C225CD3	C^{cr}	28	31	46	.10317	.10729	.10777	4.2	6.4	8.6
	D^{cr}	21	26	37	.07715	.09137	.07675			
3C20EF3	E^{cr}	34	36	36	.17134	.17664	.18147	4.3	7.8	9.2
	F^{cr}	55	56	56	.25000	.26332	.26707			
6U225AB3	A	36	46	46	.20246	.21223	.21452	3.9	6.0	7.2
	B	50	50	50	.23817	.25794	.25736			
6C225CD3	C	22	28	30	-	-	-	4.9	8.0	9.4
	D	22	23	24	.06379	.07602	.07609			
6C225EF3	E	24	24	26	.06114	.06939	.07446	5.2	7.8	10.1
	F	34	34	36	.05879	.06524	.06799			
6C20AB275	A	34	34	40	.14320	.09019	.09090	7.0	10.4	15.2
	B	32	32	32	.06838	.07469	.07437			

TR= Transfer, 7D= 7 Days, 28D= 28 Days, ^{cr}=Denotes Cracked End, ^{L}=49 Days
- = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens 3C225AB3, 3C225CD3, 3C20EF3, 6U225AB3, 6C225CD3, 6C225EF3, and 6C20AB275

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
6C225CD275	C	-	-	-	.06574	.07359	.07204	-	-	-
	D	-	-	-	.06713	.07841	.07572			
6C225EF275	E	18	21	22	.06396	.07172	.07059	6.0	10.0	14.8
	F	12	13	16	.06206	.06333	.05956			
6U20AB25	A	57	57	57	.12985	.14080	.13960	6.9	10.0	13.2
	B	51	51	51	-	-	-			
6C20CD25	C	32	32	32	.06045	.06604	.06322	7.2	10.9	15.0
	D	21	21	21	.06198	.08109	.06819			
6C225EF25	E	18	21	22	.05444	.06496	.06105	6.1	10.4	14.4
	F	23	34	37	.06916	.07242	.07031			

TR= At Transfer, 7D= At 7 Days, 28D= At 28 Days, - = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens 6C225CD275, 6C225EF275, 6U20AB25, 6C20CD25, and 6C225EF25

Beam ID	End	Transfer Length (in.)			Average End Slip (in.)			Effective Strain (X 10^{-4} in/in)		
		TR	7D	28D	TR	7D	28D	TR	7D	28D
U1625AB0	A	42	44	49^{t}	.20064	-	$.20359^{t}$	5.4	9.4	13.0
	B	52	53	54^{t}	.19319	-	$.19194^{t}$			
C1625CD0	C	-	-	-	.05984	-	$.06359^{t}$	-	-	-
	D	-	-	-	.05134	-	$.05634^{t}$			
C1625EF0	E	26	26	38^{t}	.06094	-	$.07594^{t}$	6.0	9.0	12.0
	F	26	28	38^{t}	.07924	-	$.07469^{t}$			
3U175AB2	A	66	67	67	.26101	.26958	.67093	7.5	12.0	14.1
	B	68	68	70	.24865	.25656	.65856			
3C175CD2	C^{cr}	65	65	65	.24935	.24976	.66303	8.1	12.1	15.0
	D^{cr}	38	38	38	.15438	.15720	.56618			
3C175EF2	E^{cr}	40	41	43	.17068	.17103	.58120	8.1	12.7	15.3
	F^{cr}	43	44	45	.15506	.15013	.55913			
3U175AB225	A	60	62	63^{t}	.25356	-	$.25706^{t}$	7.1	10.5	14.4
	B	66	66	66^{t}	.25844	-	$.25900^{t}$			

TR= Transfer, 7D= 7 Days, 28D= 28 Days, ^{cr}=Denotes Cracked End, ^{t}=49 Days
- = No Data Available

Measured Transfer Length, End Slip and Effective Strain for Specimens U1625AB0, C1625CD0, C1625EF0, 3U175AB2, 3C175EF2,and 3U175AB225

APPENDIX D

END SLIP MEASUREMENTS

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
U15AB0	B2	A	.21025	-	-
	B2	B	-	-	-
U15CD0	B2	C	-	-	-
	B2	D	-	-	-
C15EF0	B2	E	-	-	-
	B2	F	.25735	-	-
C15GH0	B2	G	.28065	-	-
	B2	H	.20385	-	-
U175AB0	B2	A	.22744	.22449	.63159
	B2	B	.29134	.27594	.68829
C175CD0	B2	C	-	-	-
	B2	D	.06314	.70504	.48314
C175EF0	B2	E	.06099	.06789	.47624
	B2	F	.12494	.13119	.54254
U1625AB0	B2	A	.20064	-	.20359^{t}
	B2	B	.19319	-	.19194^{t}
C1625CD0	B2	C	.05984	-	.06359^{t}
	B2	D	.05134	-	.05634^{t}
C1625EF0	B2	E	.06094	-	.07594^{t}
	B2	F	.07924	-	.07469^{t}

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS,
28D= 28DAYS -= NO DATA AVAILABLE
^{t}= MEASUREMENTS AT 49 DAYS

End Slip Measurements for Single Strand Specimens

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3U175AB2	B1	A	.24531	.26906	.65466
	B2	A	.29957	.30062	.71032
	B3	A	.23817	.23907	.64782
	B1	B	.22421	.22306	.63111
	B2	B	.27332	.29552	.68532
	B3	B	.24762	.25112	.65927
3C175CD2	B1	C	.31441	.28611	.73006
	B2	C	.27392	.29617	.68442
	B3	C	.15972	.16702	.57462
	B1	D	.13091	.13406	.54241
	B2	D	.17242	.17227	.57897
	B3	D	.15982	.16527	.57717
3C175EF2	B1	E	.18276	.17661	.59826
	B2	E	.17607	.17712	.57727
	B3	E	.15322	.15397	.56807
	B1	F	.15826	.14261	.55081
	B2	F	.10692	.10407	.51122
	B3	F	.20002	.20372	.61537

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS

End Slip Measurements for Specimens 3U175AB2, 3C175CD2, 3C175EF2

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	49D
3U175AB225	B1	A	.24758	-	.24858
	B2	A	.28410	-	.29785
	B3	A	.22900	-	.22475
	B1	B	.25308	-	.25418
	B2	B	.27735	-	.28167
	B3	B	.24490	-	.24115
3C175CD225	B1	C	.16393	-	.16678
	B2	C	.16220	-	.16955
	B3	C	.11165	-	.11555
	B1	D	.13823	-	.14278
	B2	D	.20510	-	.21455
	B3	D	.26275	-	.26645
3C175EF225	B1	E	.14083	-	.14438
	B2	E	.17110	-	.17935
	B3	E	.13960	-	.14790
	B1	F	.19788	-	.20683
	B2	F	.19655	-	.21435
	B3	F	.18975	-	.19860

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS,
49= 49DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 3U175AB225, 3C175CD225, 3C175EF225

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3U175AB25	B1	A	.19024	.18169	.18319
	B2	A	.18637	.18717	.18727
	B3	A	.20237	.20347	.21417
	B1	B	.22434	.22859	.22409
	B2	B	.20527	.19907	.20142
	B3	B	.24572	.24332	.24067
3C175CD25	B1	C	.14984	.15474	.14859
	B2	C	.07652	.08657	.08112
	B3	C	.06867	.07152	.07632
	B1	D	.15329	.15839	.15714
	B2	D	.14472	.15027	.15912
	B3	D	.16717	.18522	.17287
3C175EF25	B1	E	.11059	.11664	.10589
	B2	E	.13492	.16222	.14292
	B3	E	.11427	.11967	.12307
	B1	F	.12569	.13069	.12379
	B2	F	.10207	.10152	.11147
	B3	F	.15217	.16192	.14052

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS

End Slip Measurements for Specimens 3U175AB25, 3C175CD25, 3C175EF25

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3U175AB225*	B1	A	.20125	.23395	.24275
	B2	A	.22049	.20294	.22059
	B3	A	.24854	.24884	.24334
	B1	B	.21970	.21330	.17911
	B2	B	.26164	.27560	.27354
	B3	B	.21024	.22789	-
3C175CD225*	B1	C	.10625	.10745	.10270
	B2	C	.15039	.13504	.13009
	B3	C	.20329	.20419	.20264
	B1	D	.19365	.20675	.19910
	B2	D	.13759	.16539	.14794
	B3	D	.09699	.10024	.09349
3C175EF225*	B1	E	.12210	.12185	.11980
	B2	E	.06484	.06919	.06829
	B3	E	.11074	.12499	.11939
	B1	F	.11100	.12370	.12340
	B2	F	.17849	.20334	.19869
	B3	F	.06279	.07074	.06514

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 3U175AB225*, 3C175CD225*, 3C175EF225*

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3C225AB275	B1	A	.09630	.09825	.09505
	B2	A	.14517	.14982	.14667
	B3	A	-	-	-
	B1	B	.05085	.06080	.05300
	B2	B	.07667	.09422	.08762
	B3	B	.06149	.07629	.07294
3C20CD275	B1	C	.14450	.15050	.14795
	B2	C	.12527	.13092	.12797
	B3	C	.10224	.10454	.09584
	B1	D	.05570	.07245	.07015
	B2	D	.04367	.06217	.06277
	B3	D	.06214	.05799	.06154
3C20EF275	B1	E	.11385	.12290	.03570
	B2	E	.13882	.09852	.10182
	B3	E	.18309	.19404	.19369
	B1	F	.08175	.09200	.09415
	B2	F	.09242	.09927	.10257
	B3	F	.05324	.06394	.06149

POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 3C225AB275, 3C20CD275, 3C20EF275

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3U20AB25	B1	A	.18232	.19782	.18642
	B2	A	.26631	.27751	.27621
	B3	A	.26643	.26043	.26153
	B1	B	-	-	-
	B2	B	-	-	-
	B3	B	-	-	-
3C20CD25	B1	C	-	-	-
	B2	C	-	-	-
	B3	C	-	-	-
	B1	D	.19442	.20202	.19907
	B2	D	.19296	.21786	.18776
	B3	D	-	-	-
3C20EF25	B1	E	.12207	.11282	.11222
	B2	E	.16116	.17256	.16061
	B3	E	.20683	.21183	.13233
	B1	F	.07917	.08292	.06452
	B2	F	.04516	.04896	.03106
	B3	F	.00138	.00888	.00623
POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS -= NO DATA AVAILABLE					

End Slip Measurements for Specimens 3U20AB25, 3C20CD25, 3C20EF25

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
3C225AB3	B1	A	.07436	.08621	.07961
	B2	A	.00206	.01601	.00416
	B3	A	-	-	-
	B1	B	.06936	.06801	.06701
	B2	B	.15081	.14076	.14256
	B3	B	.10410	.11405	.10730
3C225CD3	B1	C	.08861	.09226	.10566
	B2	C	.12336	.13206	.13251
	B3	C	.09755	.09755	.08515
	B1	D	.06936	.07851	.03891
	B2	D	.09521	.10941	.10611
	B3	D	.06690	.08620	.08525
3C20EF3	B1	E	.13596	.12291	.12396
	B2	E	.17936	.19451	.20421
	B3	E	.19870	.21250	.21625
	B1	F	.22116	.24341	.24561
	B2	F	-	-	-
	B3	F	.27880	.28320	.28850
POS=POSITION, TR=AT TRANSFER, 7D= 7 DAYS, 28D= 28DAYS -= NO DATA AVAILABLE					

End Slip Measurements for Specimens 3C225AB3, 3C225CD3, 3C20EF3

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
6U225AB3	A1	A	.27763	.29568	.29458
	A2	A	.28473	.31203	.32363
	A3	A	-	-	-
	B1	A	.15330	.14355	.13780
	B2	A	.15033	.16843	.16943
	B3	A	.14619	.14134	.14704
	A1	B	.28413	.33848	.33143
	A2	B	.33323	.37743	.37213
	A3	B	.32037	.37372	.37912
	B1	B	.16585	.16145	.15965
	B2	B	.13288	.14093	.14288
	B3	B	.19254	.15559	.15894
6C225CD3	A1	C	-	-	-
	A2	C	-	-	-
	A3	C	-	-	-
	B1	C	-	-	-
	B2	C	-	-	-
	B3	C	-	-	-
	A1	D	.05063	.06018	.07842
	A2	D	.08443	.11048	.10928
	A3	D	.06347	.07852	.07312
	B1	D	.05310	.06155	.05905
	B2	D	.06223	.07203	.08093
	B3	D	.06884	.07334	.06994

POS=POSITION, TR=TRANSFER, 7D=7 DAYS,
28D=28 DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 6U225AB3, and 6C225CD3

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
6C225EF3	A1	E	.05363	.05423	.05378
	A2	E	.07773	.08338	.10128
	A3	E	.09562	.11022	.11222
	B1	E	.02440	.03860	.04172
	B2	E	.04978	.05808	.06358
	B3	E	.06479	.07184	.07419
	A1	F	.11673	.12773	.14383
	A2	F	.11973	.11713	.13988
	A3	F	.06302	.08517	.08062
	B1	F	.02350	.02480	.01600
	B2	F	.00198	.00903	.00008
	B3	F	.02774	.02759	.02749
6C20AB275	A1	A	.13883	.14623	.15063
	A2	A	.09819	.11054	.10414
	A3	A	.11992	.13127	.13542
	B1	A	.03408	.03868	.03878
	B2	A	.00241	.07026	.06766
	B3	A	.46576	.04421	.04876
	A1	B	.09123	.10363	.10143
	A2	B	.08559	.11039	.11284
	A3	B	.07122	.07492	.07617
	B1	B	.05793	.05233	.05108
	B2	B	.06361	.05601	.05361
	B3	B	.04066	.05081	.05106

POS=POSITION, TR=TRANSFER, 7D=7 DAYS, 28D=28 DAYS

End Slip Measurements for Specimens 6C225EF3, and 6C20AB275

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
6C225CD275	A1	C	.05883	.06908	.06418
	A2	C	.09674	.11819	.12369
	A3	C	.09462	.09642	.09572
	B1	C	.05788	.05778	.05708
	B2	C	.03561	.03961	.03466
	B3	C	.05071	.06041	.05691
	A1	D	.09918	.11208	.11263
	A2	D	.08259	.10554	.09849
	A3	D	.08582	.09827	.09817
	B1	D	.05293	.06388	.05933
	B2	D	.03761	.04566	.04441
	B3	D	.04461	.04501	.04126
6C225EF275	A1	E	.05693	.07443	.07468
	A2	E	.05594	.07594	.07919
	A3	E	.08087	.06617	.06932
	B1	E	.05728	.06098	.06103
	B2	E	.07951	.08811	.08281
	B3	E	.05321	.06466	.05651
	A1	F	.04223	.04318	.04458
	A2	F	.05959	.06829	.06884
	A3	F	.07642	.06787	.06482
	B1	F	.08448	.09168	.08258
	B2	F	-	-	-
	B3	F	.04746	.04551	.03686

POS=POSITION, TR=TRANSFER, 7D=7 DAYS,
28D=28 DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 6C225CD275, and 6C225EF275

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
6U20AB25	A1	A	.12985	.14080	.13960
	A2	A	–	–	–
	A3	A	–	–	–
	B1	A	–	–	–
	B2	A	–	–	–
	B3	A	–	–	–
	A1	B	–	–	–
	A2	B	–	–	–
	A3	B	–	–	–
	B1	B	–	–	–
	B2	B	–	–	–
	B3	B	–	–	–
6C20CD25	A1	C	.05895	.07340	–
	A2	C	.08695	.09985	.10130
	A3	C	–	–	–
	B1	C	.04426	.05231	.05131
	B2	C	.06027	.05107	.04962
	B3	C	.05168	.05343	.05053
	A1	D	.07405	.08475	.08366
	A2	D	.09495	.18600	.10810
	A3	D	.07609	.07904	.07714
	B1	D	.03696	.05251	.05576
	B2	D	.04667	.05097	.05022
	B3	D	.04313	.03323	.03423

POS=POSITION, TR=TRANSFER, 7D=7 DAYS,
28D=28 DAYS -= NO DATA AVAILABLE

End Slip Measurements for Specimens 6U20AB25, and 6C20CD25

BEAM ID	POS	END	END SLIP (IN)		
			TR	7D	28D
6C225EF25	A1	E	.05395	.07460	.07885
	A2	E	.06670	.07855	.08015
	A3	E	.05344	.06139	.04159
	B1	E	.05466	.06516	.06106
	B2	E	.05982	.05137	.05247
	B3	E	.03803	.05863	.05213
	A1	F	.09330	.09090	.08255
	A2	F	.09610	.10175	.10090
	A3	F	.07209	.07639	.07374
	B1	F	.05561	.06306	.06221
	B2	F	.05567	.05902	.05852
	B3	F	.04218	.04338	.04393
POS=POSITION, TR=TRANSFER, 7D=7 DAYS, 28D=28 DAYS -= NO DATA AVAILABLE					

End Slip Measurements for Specimen 6C225EF25

APPENDIX E

AASHTO AVERAGE CALCULATED f_{se} AND CALCULATED TRANSFER LENGTHS

Beam ID	f_{se} (ksi)	AASHTO Equation Transfer Length (in.)
U15AB0	-	-
U15CD0	-	-
C15EF0	-	-
C15GH0	-	-
U175AB0	181.9	30.3
C175CD0	183.6	30.6
C175EF0	181.9	30.3
U1625AB0	183.6	30.6
C1625CD0	-	-
C1625EF0	181.9	30.3
3U175AB2	175.0	29.2
3C175CD2	173.3	28.9
3C175EF2	173.3	28.9
3U175AB225	173.3	29.6
3C175CD225	175.3	29.2
3C175EF225	175.6	29.3
3U175AB25	192.2	32.0
3C175CD25	191.3	31.9
3C175EF25	189.0	31.5
3U175AB225*	190.5	31.8
-= NO DATA AVAILABLE		

AASHTO Calculated Transfer Lengths and f_{se}

Beam ID	f_{se} (ksi)	AASHTO Equation Transfer Length (in.)
3C175CD225*	196.8	32.8
3C175EF225*	188.5	31.4
3C225AB275	197.6	32.9
3C20CD275	197.1	32.9
3C20EF275	197.6	32.9
3U20AB25	197.9	33.0
3C20CD25	193.9	32.3
3C20EF25	195.9	32.7
3C225AB3	196.2	32.7
3C225CD3	196.2	32.7
3C20EF3	195.9	32.7
6U225AB3	194.5	32.4
6C225CD3	191.6	31.9
6C225EF3	190.8	31.8
6C20AB275	187.0	31.2
6C225CD275	-	-
6C225EF275	189.9	31.7
6U20AB25	191.0	31.8
6C20CD25	190.2	31.7
6C225EF25	193.3	32.2

-= NO DATA AVAILABLE

AASHTO Calculated Transfer Lengths and f_{sc}

APPENDIX F

MEASURED END SLIPS, CALCULATED END SLIPS, AND RATIO OF MEASURED TO CALCULATED END SLIPS

Beam ID	End	Average End Slip (in.)		Ratio Measured/ Calculated
		Measured	Calculated	
U175AB0	A	.22774	.23664	0.962
	B	.29134	.31008	0.940
C175CD0	C	–	.07722	–
	D	.06314	.08844	0.714
C175EF0	E	.06099	.09792	0.623
	F	.12494	.09792	1.276
U1625AB0	A	.20064	.14622	1.373
	B	.19319	.18096	1.068
C1625EF0	E	.06094	.09048	0.674
	F	.07924	.09048	0.876
3U175AB2	A	.26101	.20188	1.293
	B	.24865	.20804	1.195
3C175CD2	C	.24935	.22327	1.117
	D	.15438	.13053	1.183
3C175EF2	E	.17068	.13740	1.242
	F	.15506	.14770	1.050
3U175AB225	A	.25356	.20730	1.223
	B	.25844	.22803	1.133
3C175CD225	C	.14592	.11401	1.280
	D	.20202	.21421	0.943
3C175EF225	E	.15051	.11747	1.281
	F	.19472	.18311	1.063
3U175AB25	A	.19299	.19683	0.980
	B	.22511	.22599	0.996
–= NO DATA AVAILABLE				

Measured and Calculated End Slips with Ratio of the Two for Specimens U175AB0, C175CD0, C175EF0, U1625AB0 C1625EF0, 3U175AB2, 3C175CD2, 3C175EF2, 3U175AB225, 3C175CD225, 3C175EF225, and 3U175AB25

Beam ID	End	Average End Slip (in.)		Ratio Measured/ Calculated
		Measured	Calculated	
3C175CD25	C	.09834	.10206	0.964
	D	.15506	.13486	1.150
3C175EF25	E	.11993	.10935	1.097
	F	.12664	.12393	1.022
3U175AB225*	A	.22342	.20075	1.113
	B	.23052	.22630	1.019
3C175CD225*	C	.15331	.10585	1.448
	D	.14274	.14600	0.978
3C175EF225*	E	.09922	.09854	1.007
	F	.11742	.11680	1.005
3C225AB275	A	.12071	.12529	0.963
	B	.06301	.09581	0.658
3C20CD275	C	.12401	.14371	0.863
	D	.05384	.08844	0.609
3C20EF275	E	.14526	.11055	1.314
	F	.07581	.10318	0.735
3U20AB25	A	.23855	.22140	1.077
	B	-	.26568	-
3C20CD25	C	-	.16605	-
	D	.19370	.10332	1.875
3C20EF25	E	.16335	.13652	1.197
	F	.04190	.06642	0.631
3C225AB3	A	.03820	.08736	0.437
	B	.10809	.09828	1.100

-= NO DATA AVAILABLE

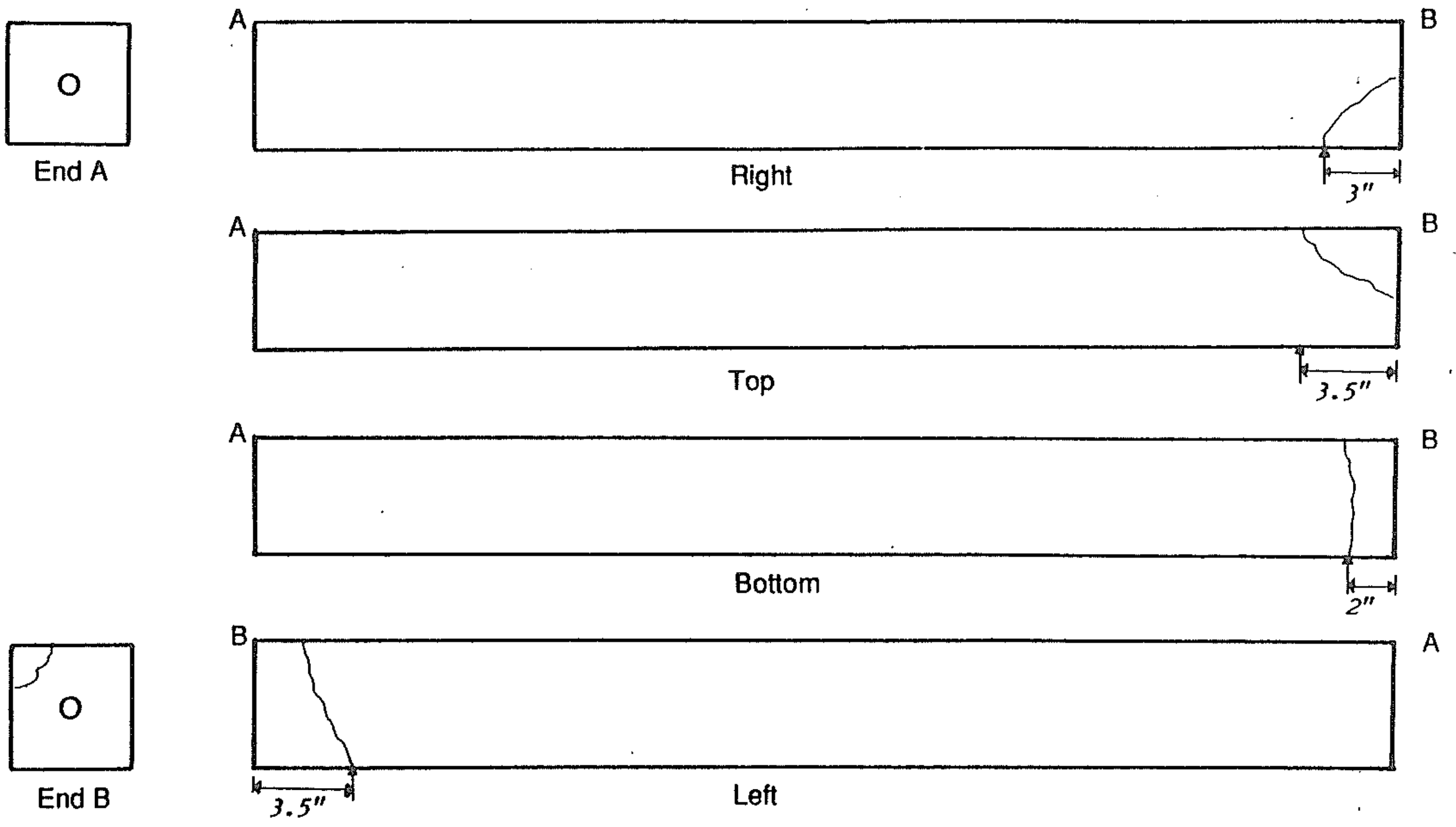
Measured and Calculated End Slips with Ratio of the Two for Specimens 3C175CD25, 3C175EF25, 3U175AB225*, 3C175CD225*, 3C175EF225*, 3C225AB275, 3C20CD275, 3C20EF275, 3U20AB25, 3C20CD25, 3C20EF25, and 3C225AB3.

Beam ID	End	Average End Slip (in.)		Ratio Measured/ Calculated
		Measured	Calculated	
3C225CD3	C	.10317	.10192	1.012
	D	.07715	.07644	1.009
3C20EF3	E	.17134	.12376	1.384
	F	.25000	.20019	1.249
6U225AB3	A	.20246	.12942	1.564
	B	.23817	.17975	1.325
6C225CD3	C	-	.07909	-
	D	.06379	.07909	0.807
6C225EF3	E	.06114	.08628	0.709
	F	.05879	.12223	0.481
6C20AB275	A	.14320	.12308	1.163
	B	.06838	.11584	0.590
6C225EF275	E	.06396	.06516	0.982
	F	.06206	.04344	1.429
6U20AB25	A	.12985	.21004	0.618
	B	-	.18793	-
6C20CD25	C	.06045	.11792	0.513
	D	.06198	.07738	0.801
6C225EF25	E	.05444	.06633	0.821
	F	.06916	.08475	0.816
-= NO DATA AVAILABLE				

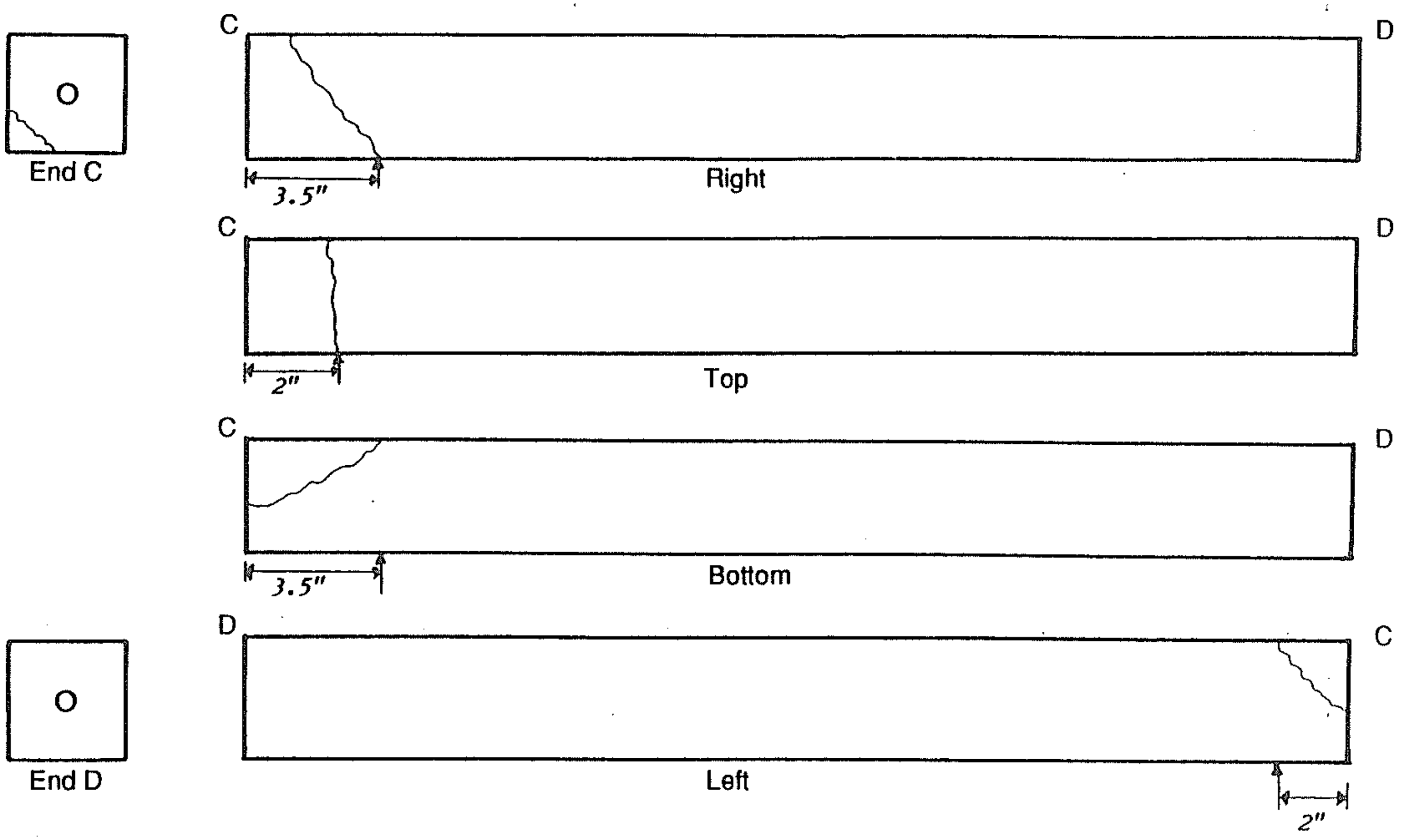
Measured and Calculated End Slips with Ratio of the Two for Specimens 3C225CD3, 3C20EF3, 6U225AB3, 6C225CD3, 6C225EF3, 6C20AB275, 6C225EF275, 6U20AB25, 6C20CD25, and 6C225EF25

APPENDIX G

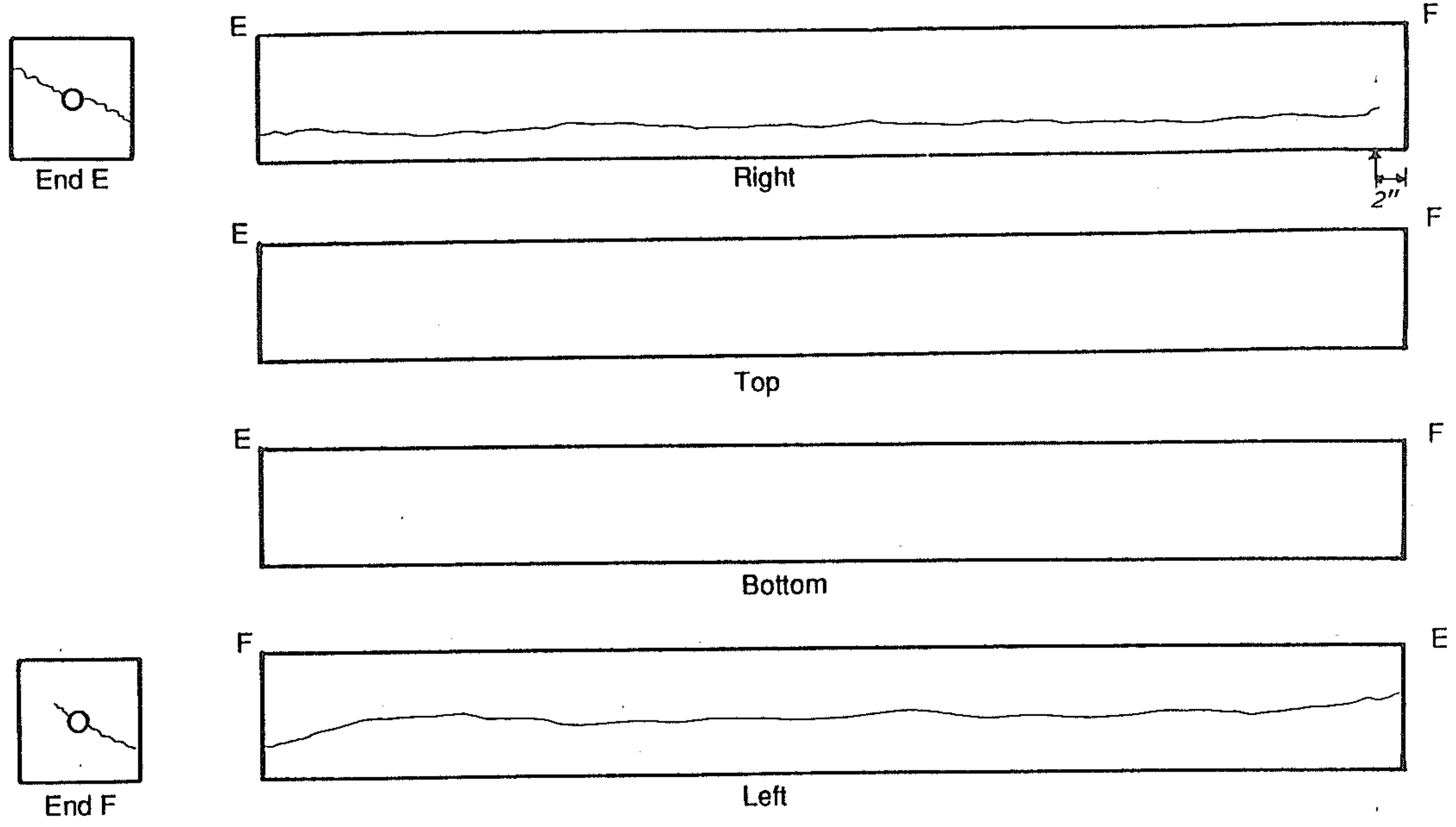
CRACK PATTERNS



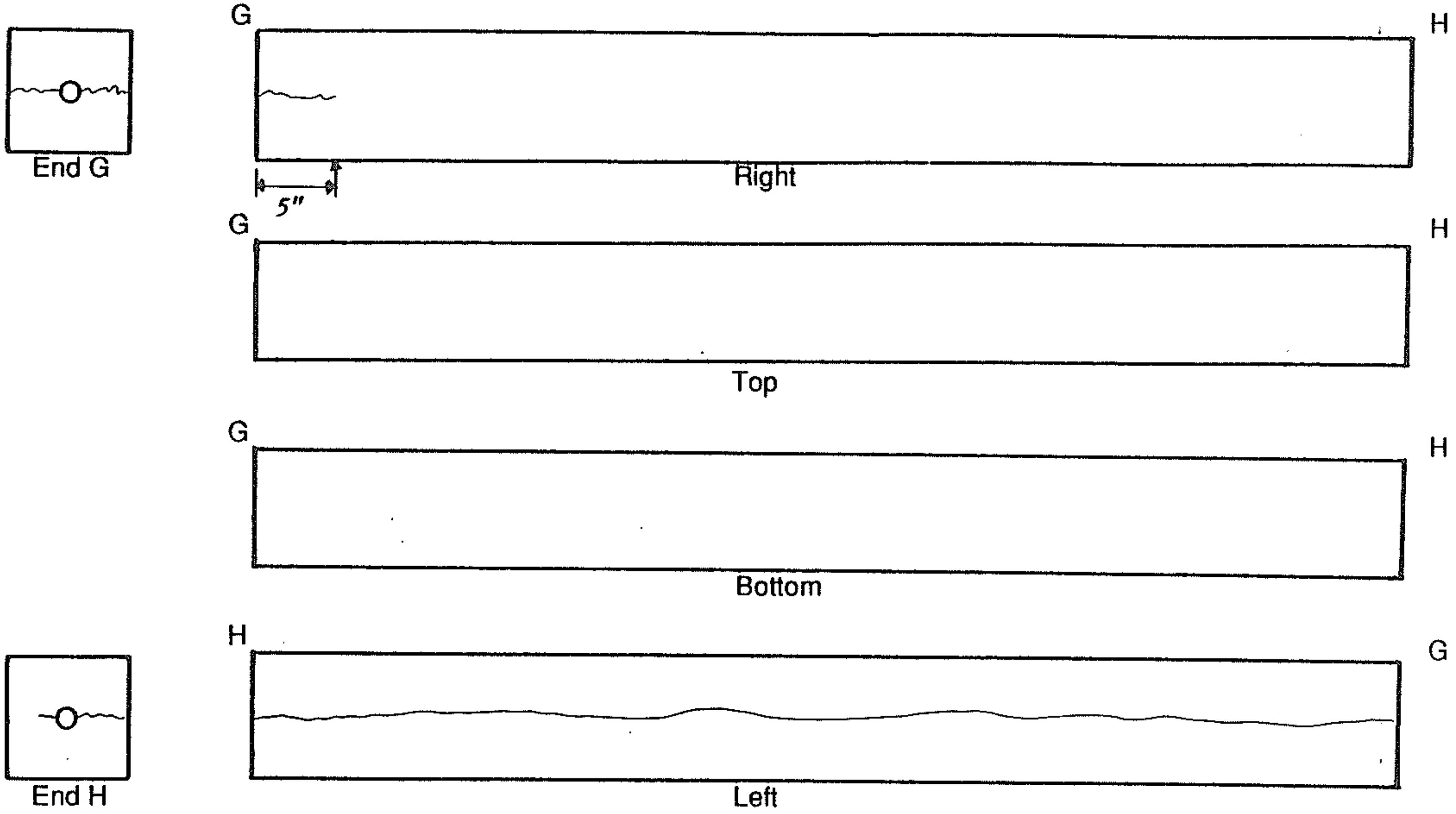
Crack Pattern for Specimen U15AB0



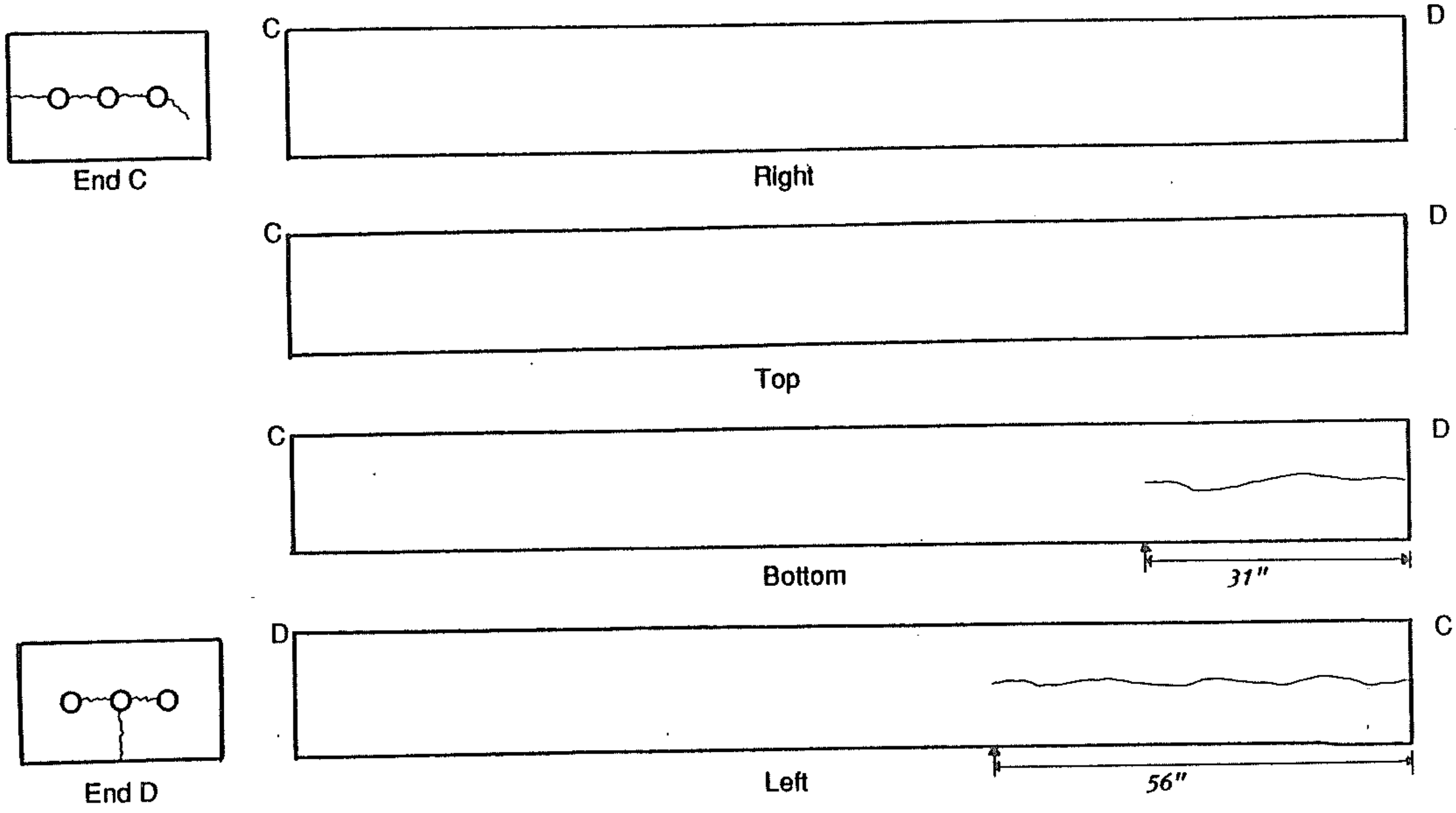
Crack Pattern for Specimen U15CD0



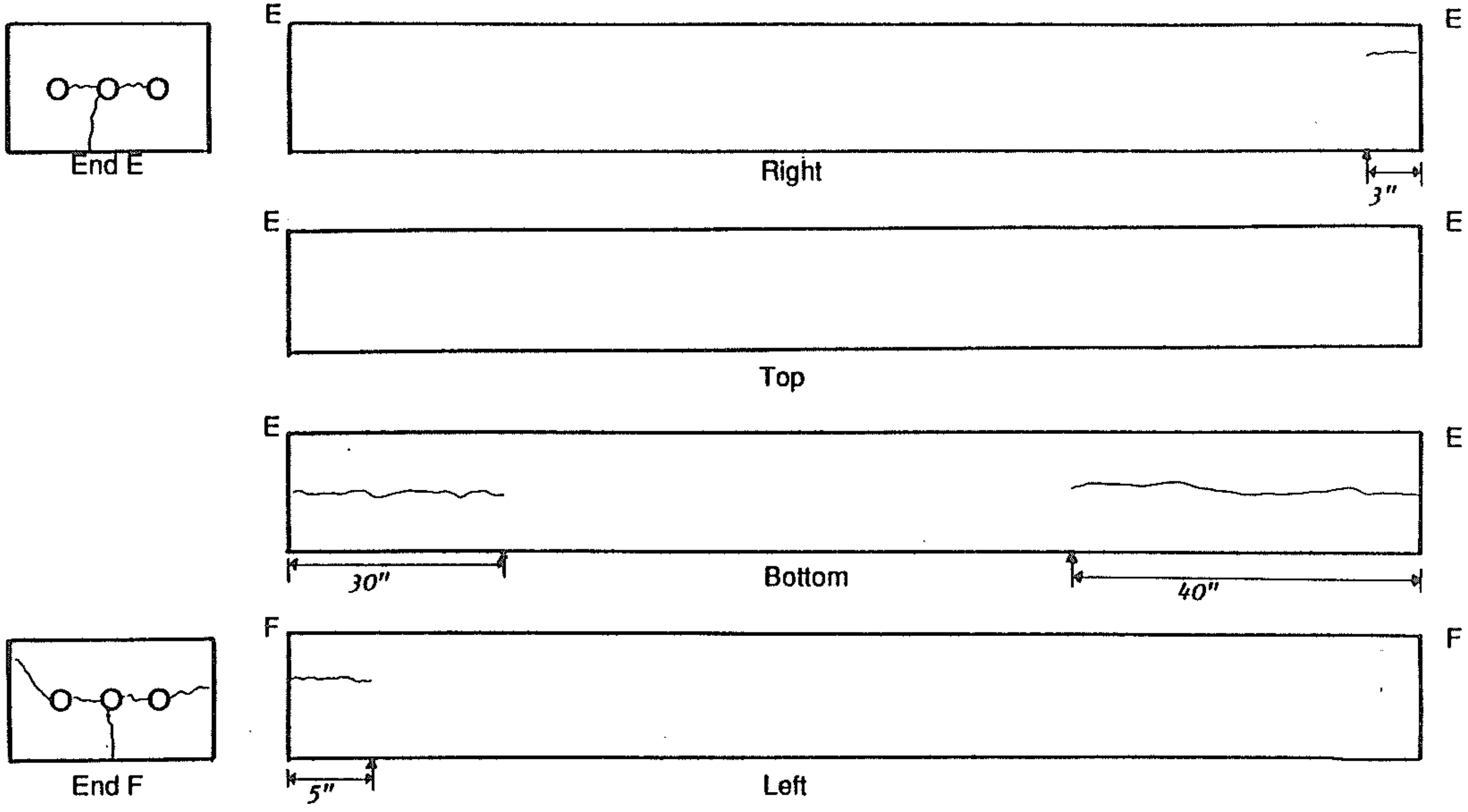
Crack Pattern for Specimen C15EF0



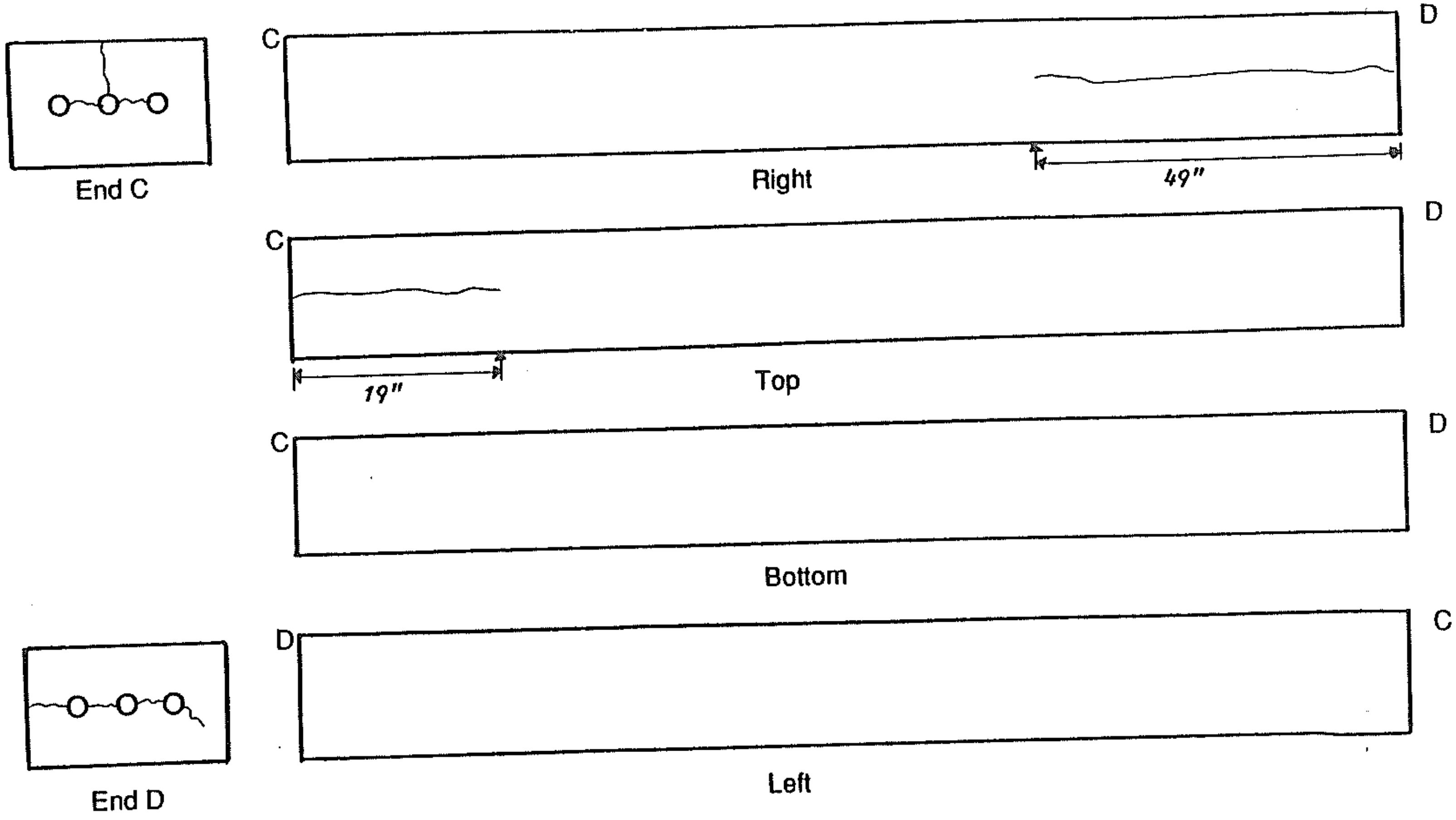
Crack Pattern for Specimen C15GH0



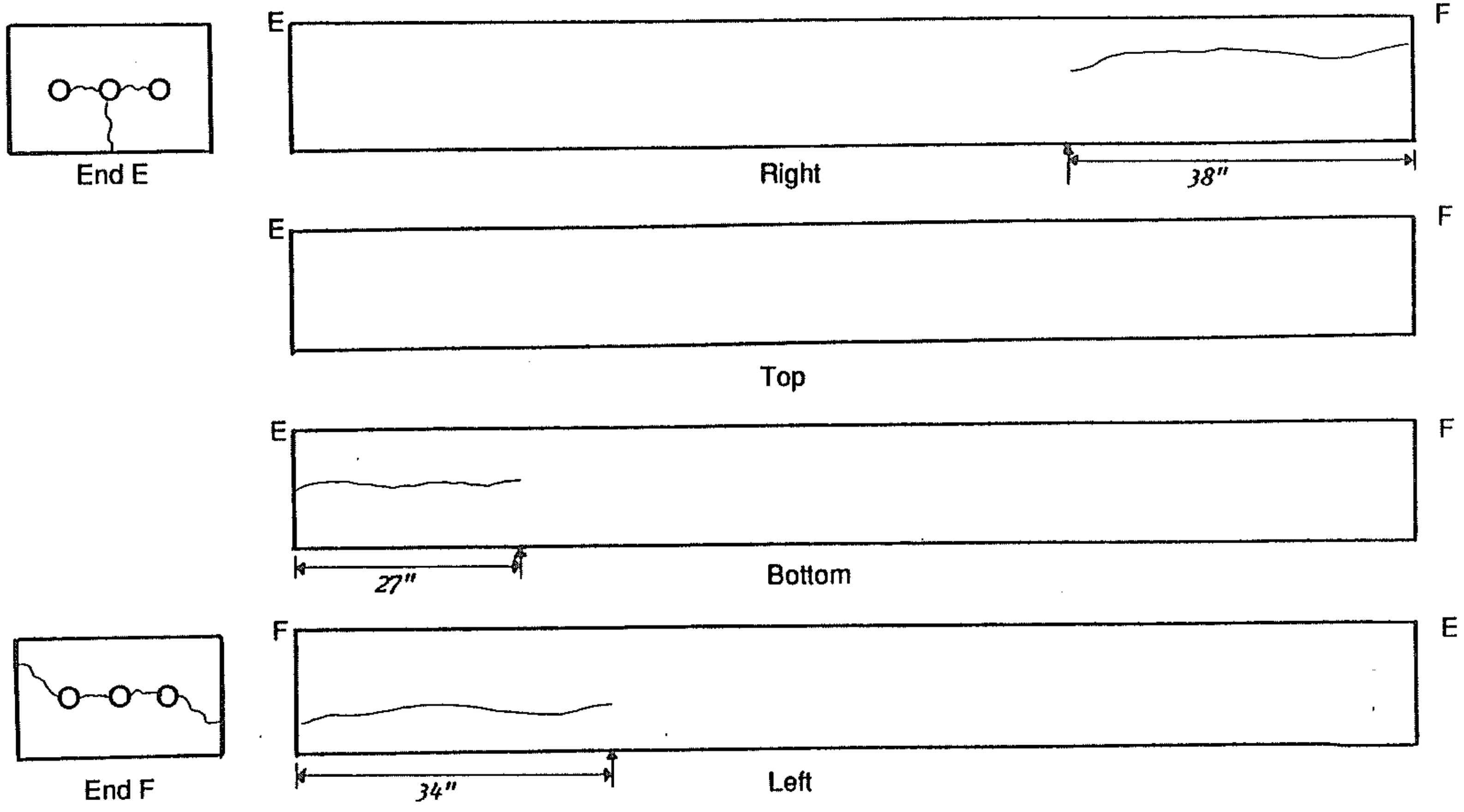
Crack Pattern for Specimen 3C175CD2



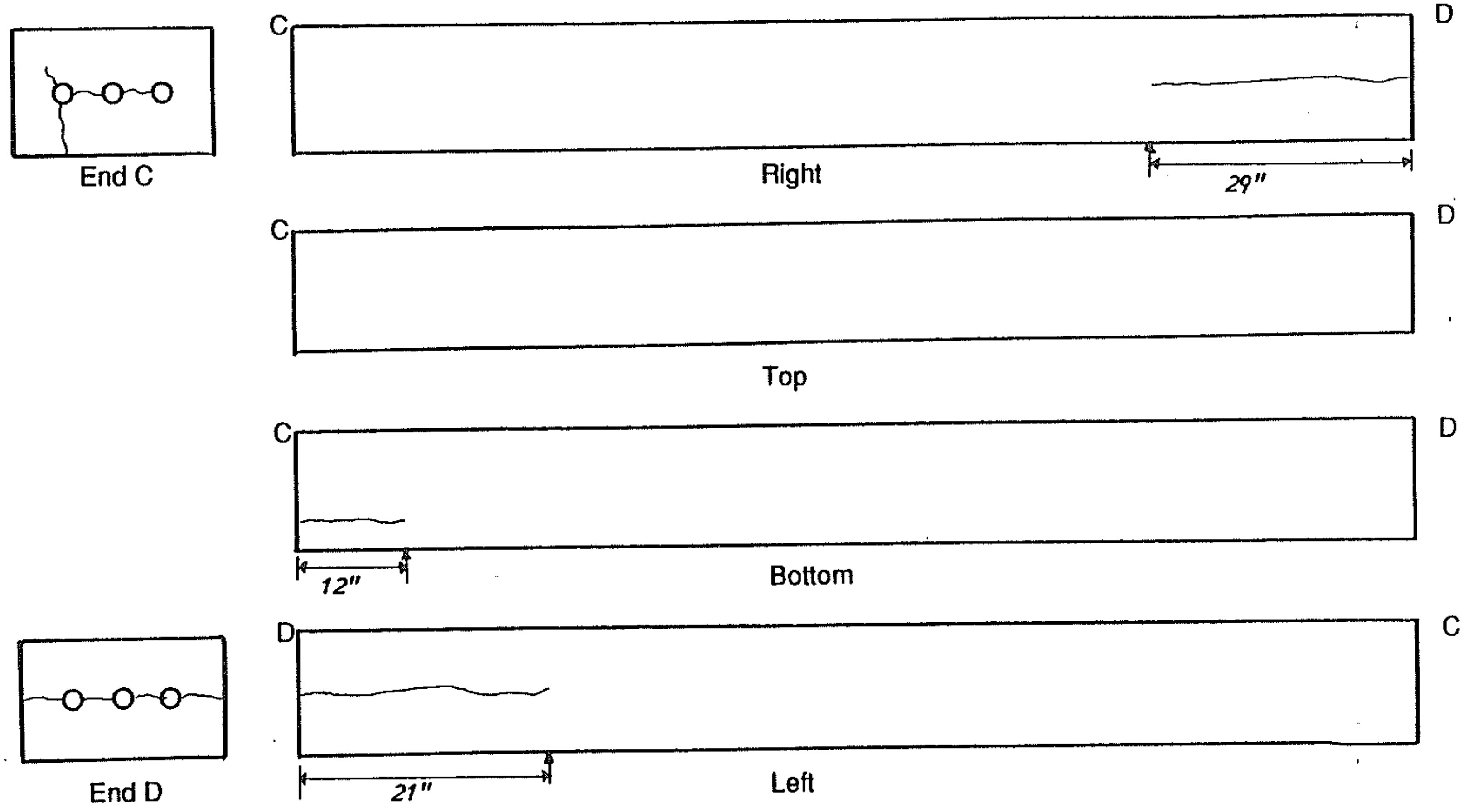
Crack Pattern for Specimen 3C175EF2



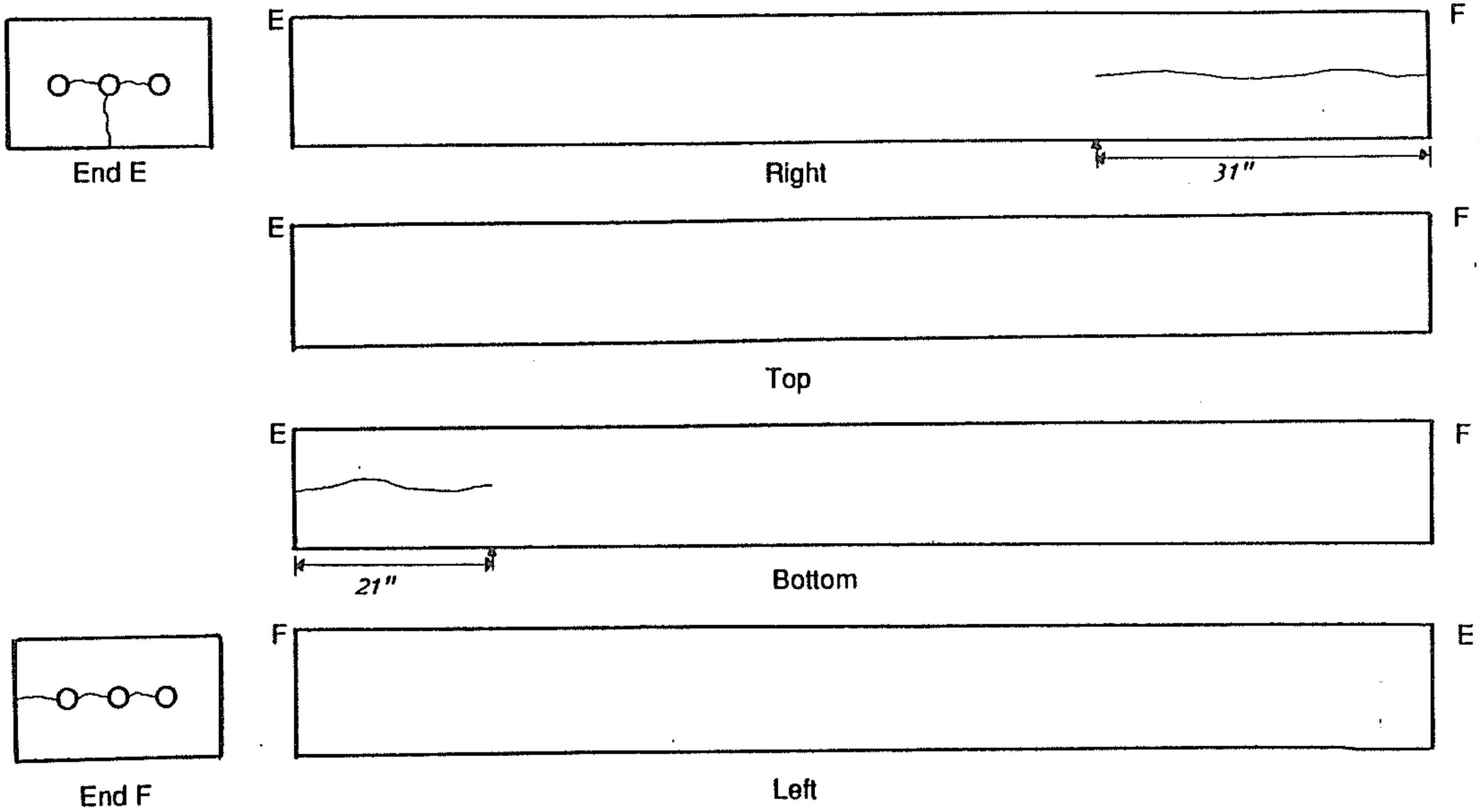
Crack Pattern for Specimen 3C175CD225



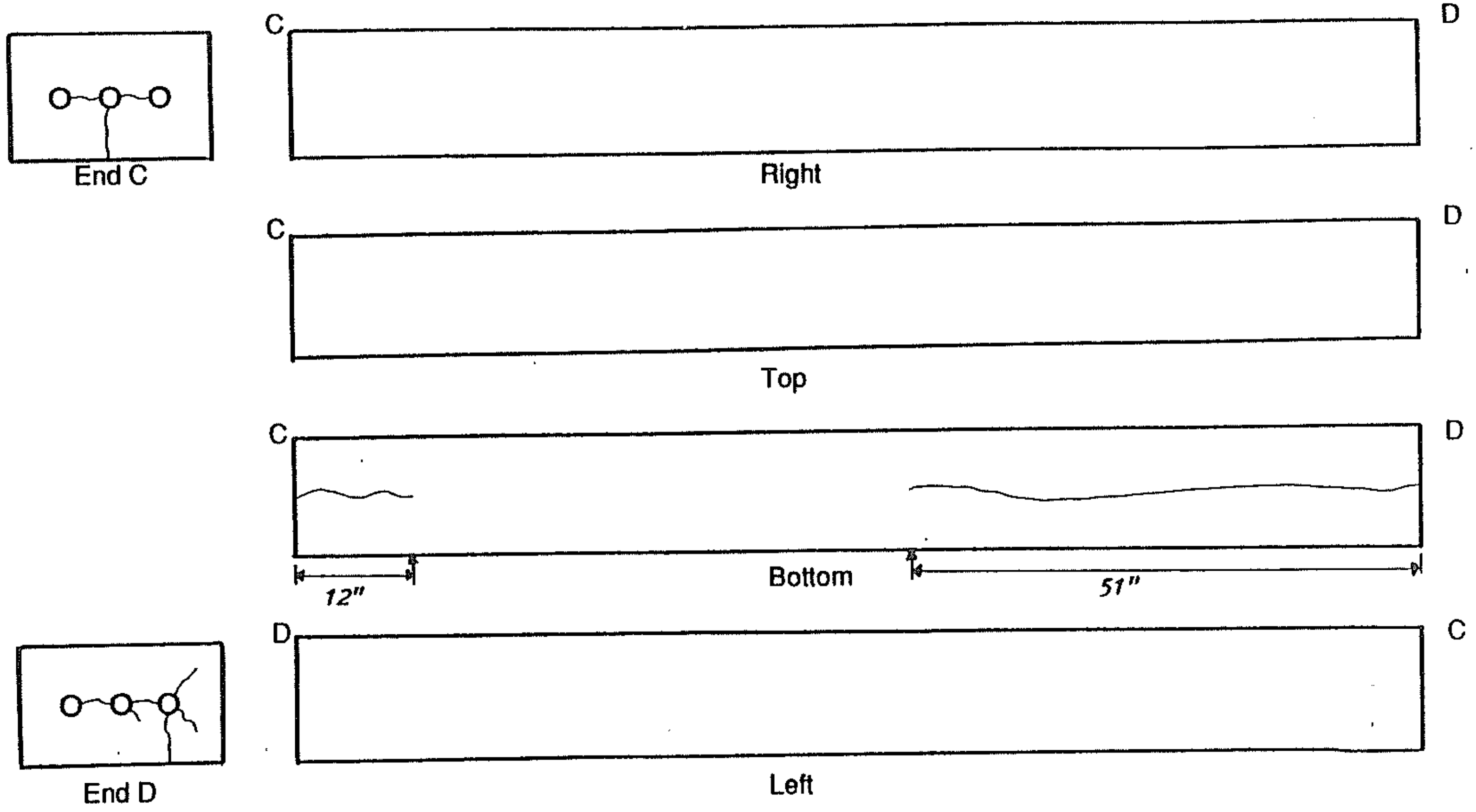
Crack Pattern for Specimen 3C175EF225



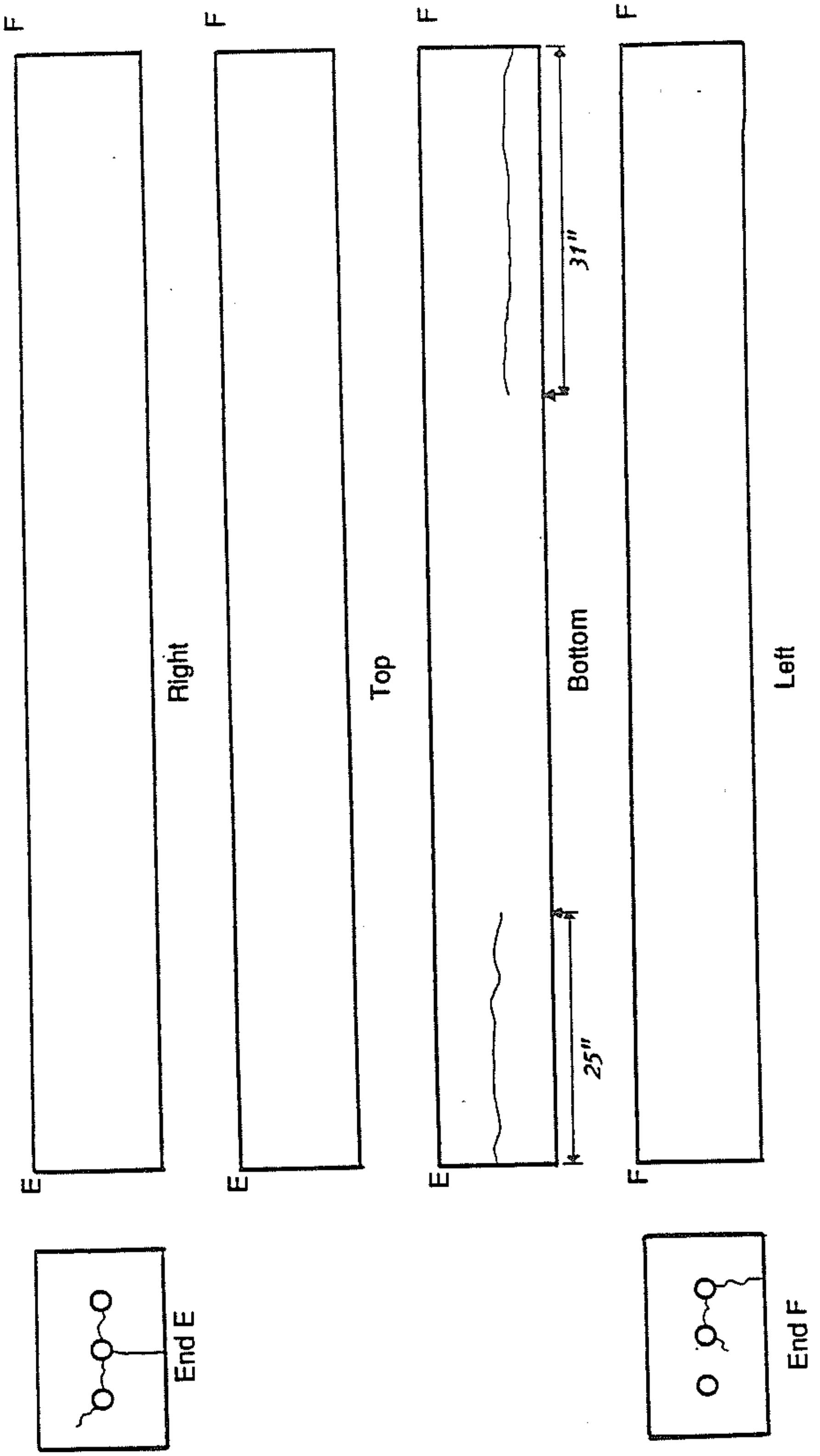
Crack Pattern for Specimen 3C175CD25



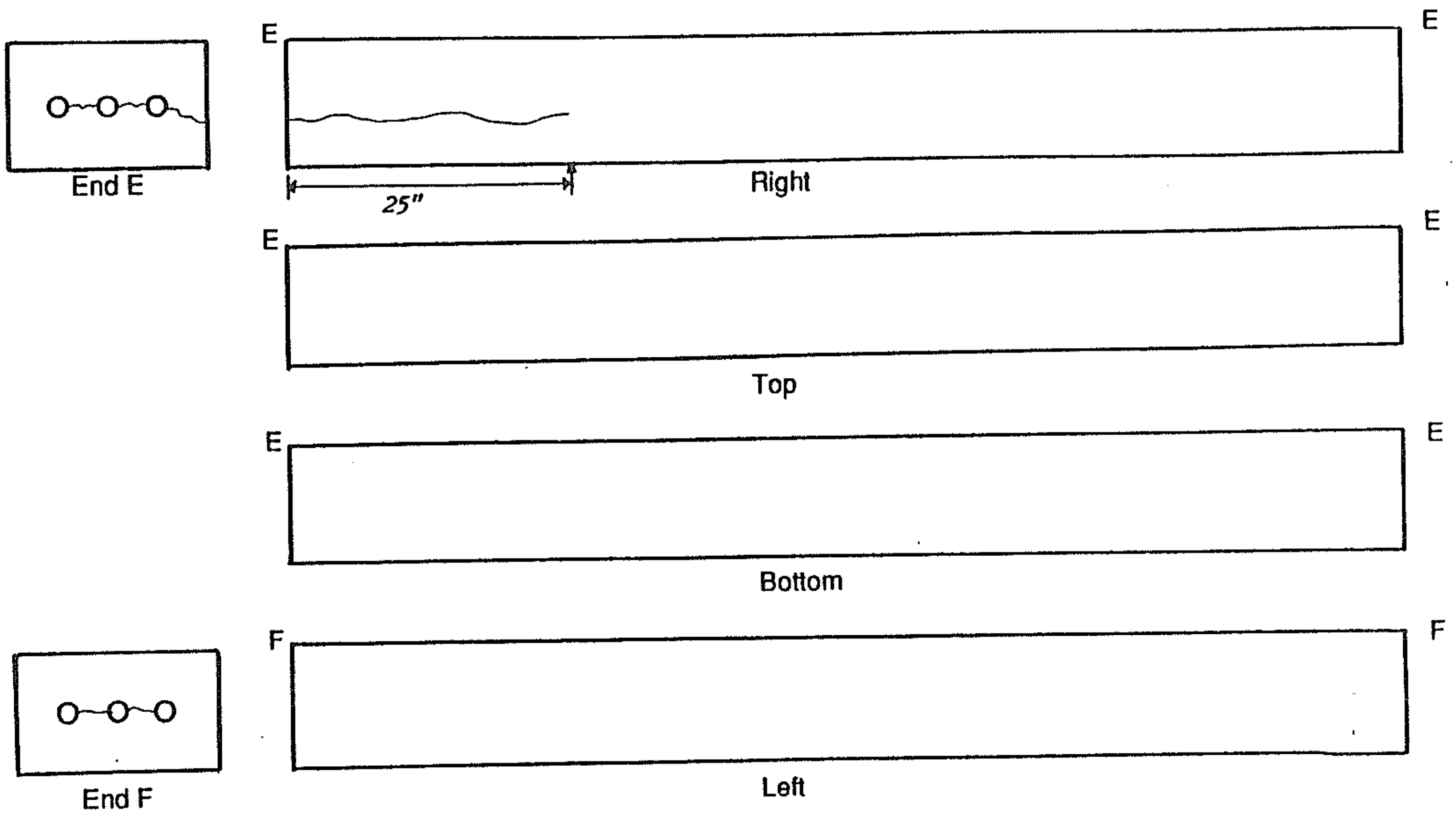
Crack Pattern for Specimen 3C175EF25



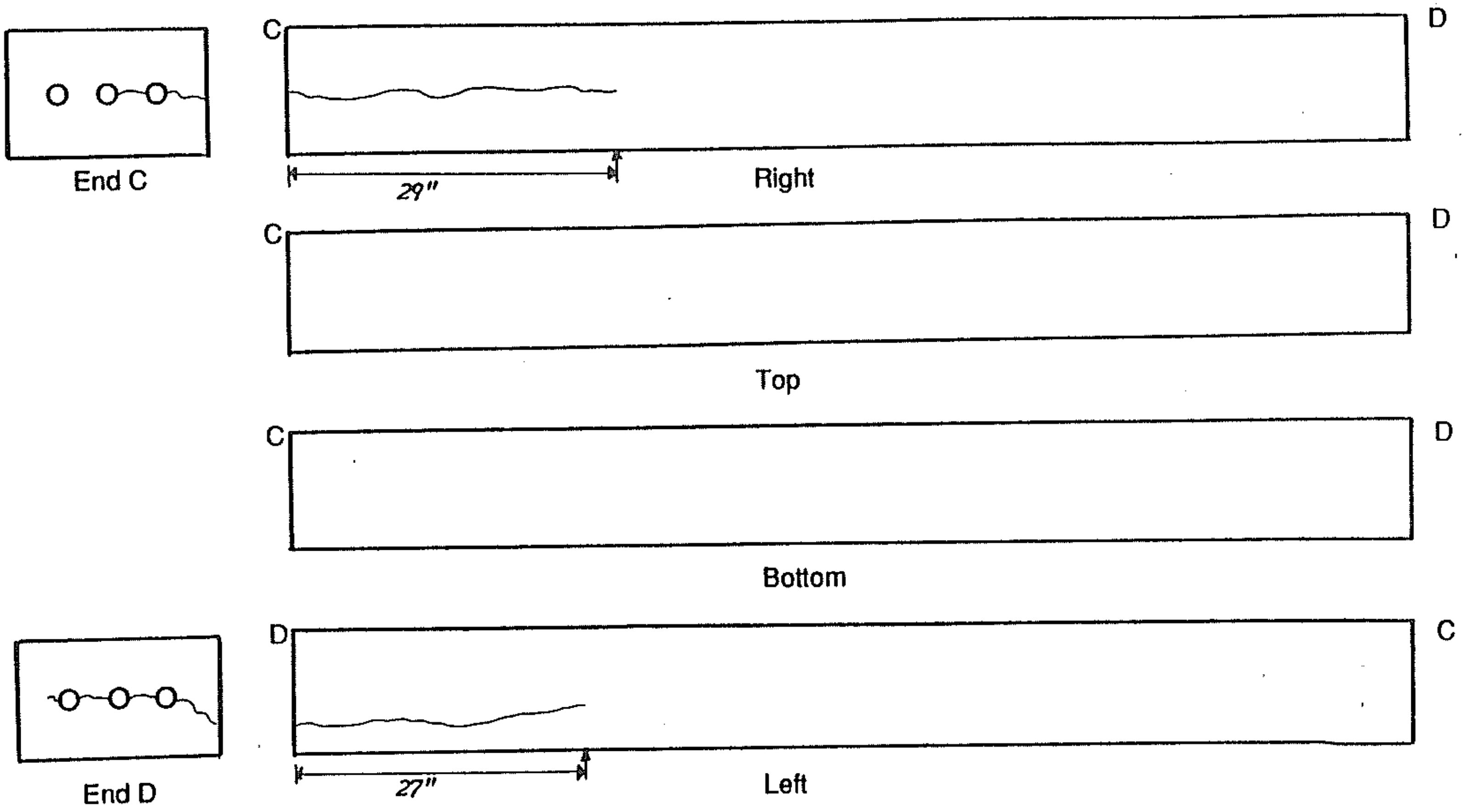
Crack Pattern for Specimen 3C175CD225*



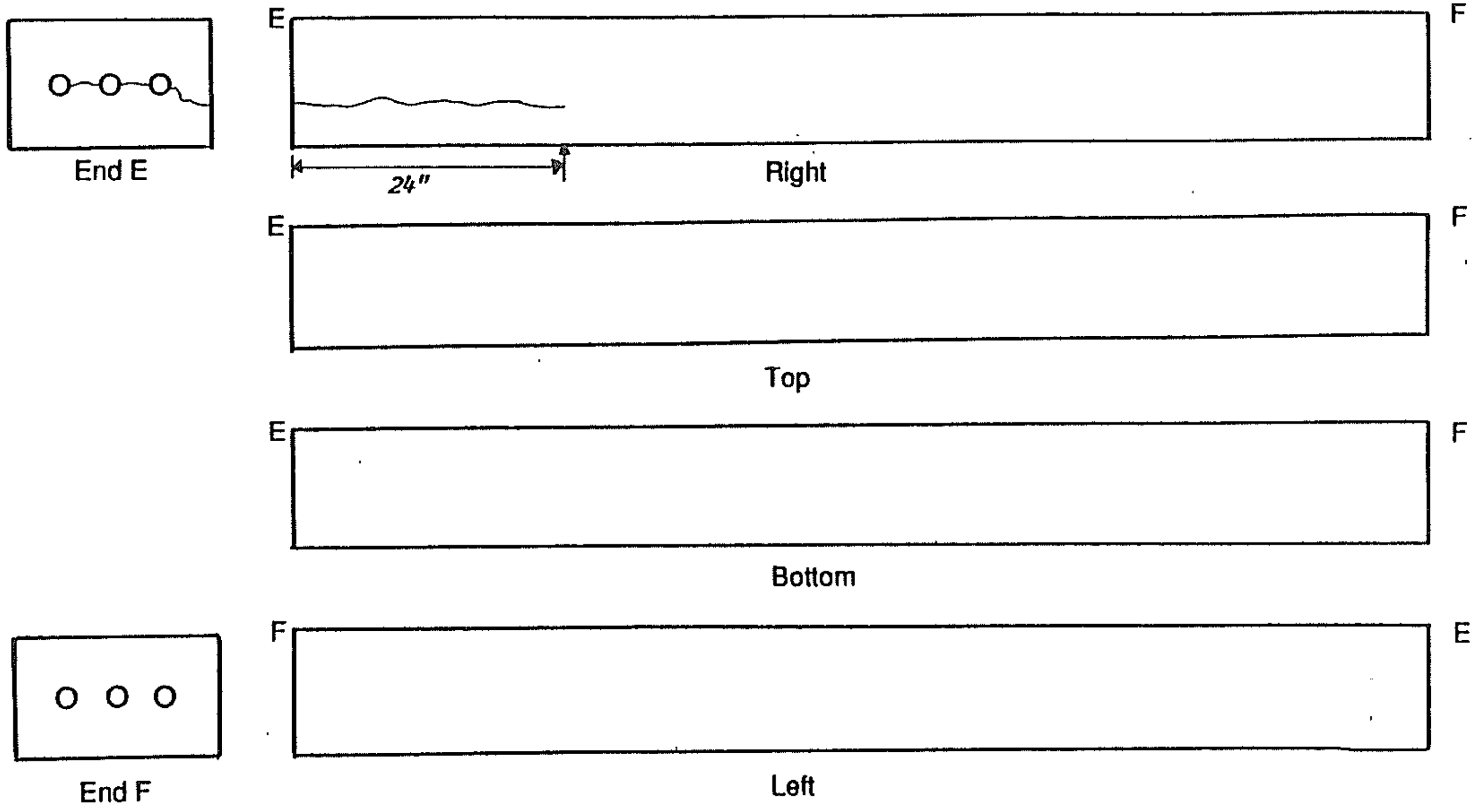
Crack Pattern for Specimen 3C175EF225*



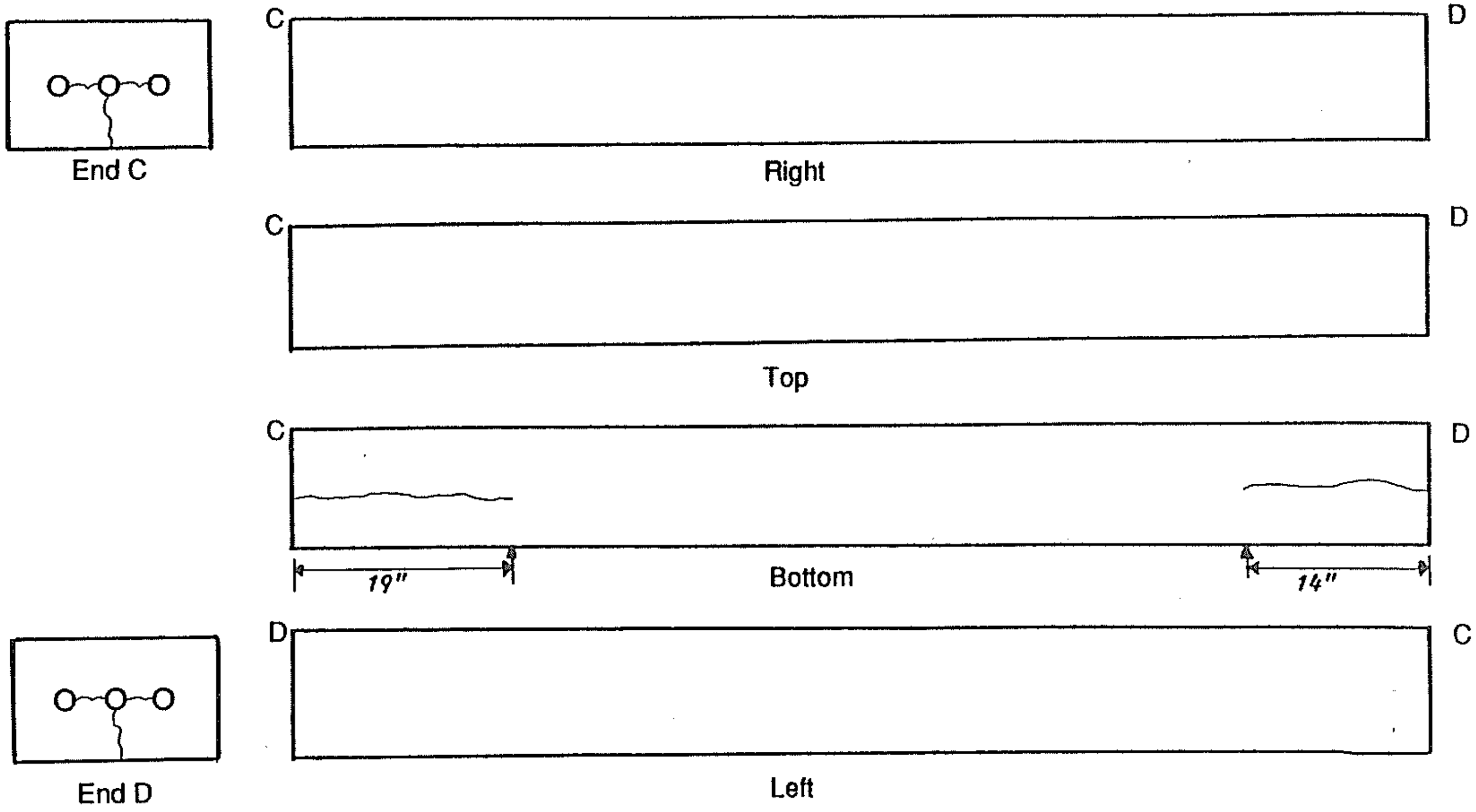
Crack Pattern for Specimen 3C20EF275



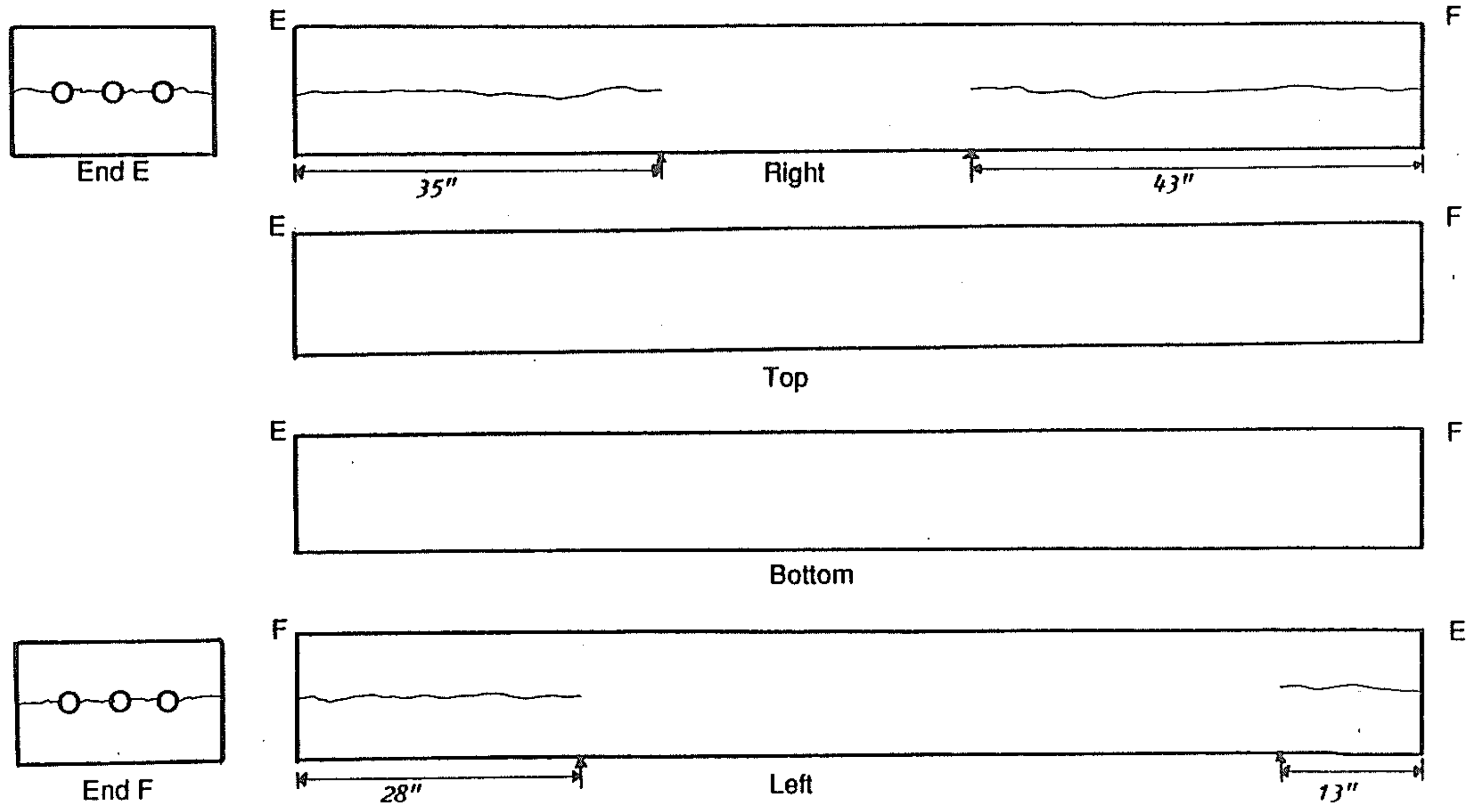
Crack Pattern for Specimen 3C20CD25



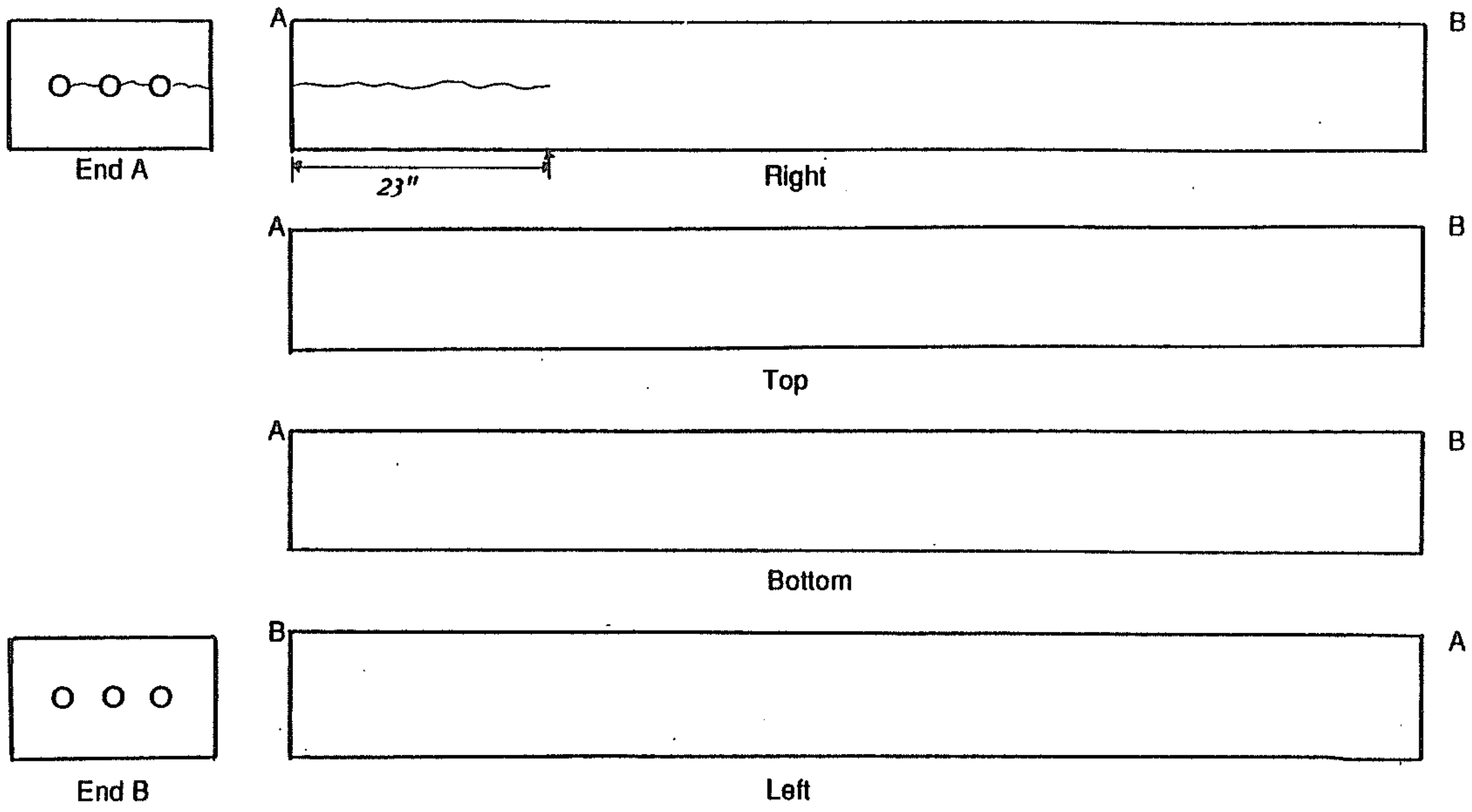
Crack Pattern for Specimen 3C20EF25



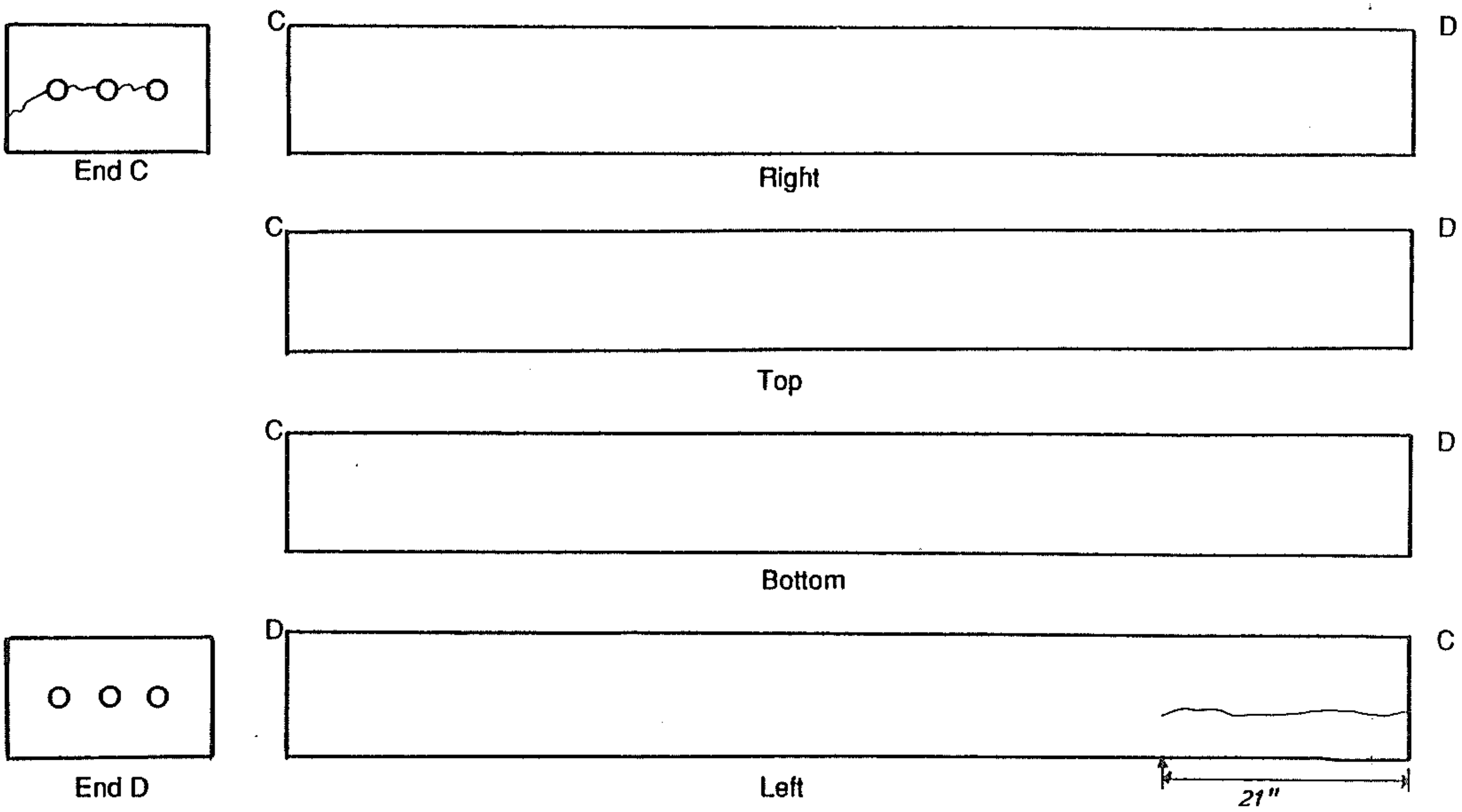
Crack Pattern for Specimen 3C225CD3



Crack Pattern for Specimen 3C20EF3



Crack Pattern for Specimen 3C225AB275



Crack Pattern for Specimen 3C2OCD275