TRANSFER AND DEVELOPMENT LENGTH OF 0.6-INCH DIAMETER PRESTRESSING STRAND AT TWO INCH SPACING IN FULLY BONDED NORMAL STRENGTH CONCRETE COMPOSITE TEXAS TYPE C BEAMS

by

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____

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To my wife

Mariela

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Carlos Córdova
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ABSTRACT

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The University of Texas at Austin, 1996

SUPERVISOR: Ned H. Burns

The purpose of this study was to determine the transfer and development length of 0.6-inch diameter prestressing strand in normal strength concrete beams. Two standard Texas Type C beams with a composite slab were fabricated. The beams had design strengths of 4300 psi at release of the prestressing force and 7000 psi at 28 days. The concrete slab had a design strength of 6000 psi at 28 days.

Transfer length was determined by measuring the concrete strain at the center of gravity of the prestressing strand at the bottom of the beams. The concrete strain occurred due to the release of the prestressing force. Development length was determined by loading each end of the two beams to failure. The embedment length, that is, the distance from the end of the beam to the first of two concentrated loads, was varied for each test. The development length tests for these two beams resulted in flexural failure with

the four tests having embedment lengths of 120, 93, 78, and 72 inches. The results are compared with design equations from current ACI 318 and AASHTO codes and previous research reports.

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CHAPTER ONE
INTRODUCTION

1.1. Background and Problem Definition

Prestressed concrete has been widely used for all kinds of structures. But its main application is found in the area of transportation with the construction of bridges, viaducts and overpasses. The rapid development of prestressed concrete was possible due to the improvement in the materials used (high strength concrete and steel) and in the methods of tensioning and end anchorages.

The use of 0.5 in. diameter prestressing strands at 2 in. spacing in precast prestressed concrete beams has been used for many years with good results. In order to take advantage of the new high strength concretes ($f'c>10000$ psi), the use of 0.6 in. diameter prestressing strands at 2 in. spacing has been proposed. But in October 1988, the Federal Highway Administration (FHWA) issued a memorandum that placed the following restrictions on the use of seven wire strands for pretensioned concrete members in highway bridge applications [1]:

- The use of 0.6 in. diameter strand in a pretensioned application shall not be allowed.
- Minimum strand spacing (center to center) will be four times the nominal strand diameter.

- Development length for all strand sizes up to and including 9/16 in. shall be determined as 1.6 times the AASHTO equation.
- Where strand is debonded (blanketed) at the end of a member and tension at service load is allowed in the precompressed tensile zone, the development shall be determined as 2 times the AASHTO equation.

As a result of this memorandum, many research projects on strand transfer and development length were initiated in the United States. The present study addresses the use of 0.6 in. diameter strands at 2 in. spacing in normal strength pretensioned prestressed concrete beams.

1.2. Objective of this Research Program

The present study is funded by the Federal Highway Administration and the Texas Department of Transportation. The objective of the research program is to determine the transfer and development lengths of 0.6 in. diameter strands spaced at 2 in. In order to accomplish this task, two normal strength concrete beams were designed with a composite cast-in-place deck of the size and strength needed to reach a strain in the prestressing steel of about 3% to 3.5%. The beams were made long enough to conduct two tests per beam, one at each end. The test beams utilized the I-shaped Texas C shape which has similar characteristics of the Type IV beams which are utilized for the North Concho River Bridge Project in San Angelo, Texas. Although the bridge uses high strength concrete for its beams, this study will provide more information for transfer and development lengths in normal strength concrete beams. A study using companion beams with high strength concrete is reported by Michael Braun [18].

1.3. Topical Outline of the Presentation

Chapter One gives a brief introduction to the study discussed in this report. Chapter Two summarizes previous studies conducted on the subject of transfer and development length. The test program is described in Chapter Three, and the results are presented in Chapter Four. A discussion of the results and the conclusions are presented in Chapter Five and Chapter Six, respectively.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

This chapter is intended to develop the basic understanding of bond in pretensioned prestressed concrete members. For that reason a summary of the different mechanisms that provide bond are briefly discussed. Then, a definition of transfer and development length is given with the many variables that affect them. Brief discussions of some of the many experimental research programs conducted over the past years is presented, and a list of proposed formulas for transfer and development length is included at the end.

2.2. Nature of Bond of Prestressed Reinforcement

There are two types of bond stresses in pretensioned prestressed concrete: transfer bond stresses and flexural or development bond stresses. The first one is responsible for transferring the forces from the strands to the concrete. The second one plays a very important role developing the increase in strand tension due to applied loads.

2.2.1. Bond Mechanisms

Three independent mechanisms contribute to the bond between the steel strand and the surrounding concrete. These are: adhesion, Hoyer’s effect and mechanical interlock.

Adhesion - Between the steel strand and the concrete an adhesive mechanism is developed which keeps both materials together. The behavior of this mechanism is rigid brittle e.g. not ductile behavior. Once the strand slips, any contribution from adhesion to the bond between the steel and the surrounding concrete is lost.

Hoyer’s effect - This mechanism was first observed by E. Hoyer who performed early research on prestressed concrete. When the steel is pretensioned a reduction in its diameter occurs which is proportional to its Poisson’s ratio. Then concrete is placed surrounding the prestressing steel. When the concrete develops enough strength, the strands are released losing their original prestress. At this point the pretensioned strand wants to recover its original form i.e. initial diameter, but the surrounding concrete impedes it from doing so. Due to this impediment, a normal force is imposed on the steel strands. This normal force activates a frictional force between the two materials. This friction acts against any relative movement of the strands with respect to the concrete, therefore the force restrains the pretensioned strand and holds it in tension.

Mechanical interlock - Seven-wire strands have a center wire larger than the outer six wires which wrap it firmly in a helical form. The hardened concrete provides perfect encasement for the strands. Therefore they cannot shorten with respect to the concrete without twisting. Movement is resisted by the narrow, raised parts of the concrete surface in contact with the strands.

2.2.2. Bond Stresses

Two types of bond stresses occur in prestressed concrete. The first is referred to as transfer bond stresses, and the second as flexural bond stresses or development bond stresses.

Transfer bond stresses have the function of transferring the force from the steel strands to the concrete. These stresses are present at the ends of a pretensioned prestressed concrete member and extend for a certain length of the strand (transfer length) until the steel stress is constant (Fig. 2.1). Transfer bond stresses are developed by Hoyer's effect and mechanical interlock. Adhesion does not contribute to bond in the transfer zone because there is slip.

Flexural bond stresses play an important role after cracking because they are responsible for developing the increase in strand tension due to external loads applied to the member. Prior to cracking, any increase in load does not significantly affect the stresses in the strands. Once a crack forms the steel stress increases dramatically at that location. Janney [2] observed that there is little interaction between the transfer bond stresses and the flexural bond stresses. Flexural bond stresses are developed from the point where the load is applied to the end of the transfer length. This length is called flexural bond length (Fig. 2.1).

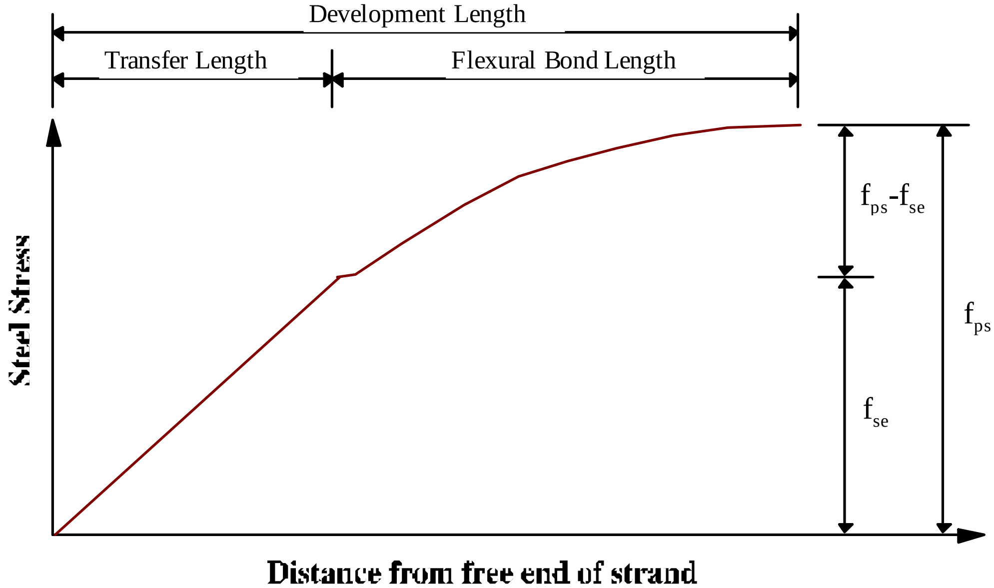


Figure 2.1. Steel Stress vs. Distance from Free End of Strand

2.2.3. General Bond Failure

The causes for a general bond failure are not well defined. Janney [2] noticed that at final bond failure the flexural bond stresses had moved outward (towards the ends of the beam) overlapping the region of the transfer bond stresses.

Hanson and Kaar [3] explain that bond failure is attributed to the reduction of the diameter of the strand in the transfer region. When flexural bond stresses reach the transfer zone, they increase the stress of the strand, so its diameter is reduced and the strand tends to slip.

Russell and Burns [4] observed that bond failure occurred when cracks propagated across the transfer zone, reaching the position of the strands.

2.3. Definitions

At this point is convenient to give some definitions about transfer length, flexural bond length, development length and embedment length.

Transfer length is the distance needed for the strand to transfer its effective prestressing force to the concrete. It can be also said that transfer length is the length of bond from the free end of the strand (where the stress is zero) to the point where the prestressing force is fully effective.

Flexural bond length is the length of bond from the point where the load is applied to the end of the transfer length. This length is responsible for developing the increase in strand tension due to external loads applied to the member.

Development length is the total length of bond required to develop the strand stress when external loads are applied to the member. Development length is taken as the algebraic sum of transfer length and flexural bond length.

Embedment length is the length of bond from the beginning of bond in the strand to the critical section. The critical section is located at the point of maximum moment where the strand stresses are maximum. The beginning of bond in fully bonded strands is located at the ends of the beam while in debonded strands, it is located where the debonding ends. In order to prevent bond failure, the embedment length should be larger than the development length.

2.4. Factors Affecting Transfer and Development Length

There are many factors that affect transfer and development length of prestressing steel. The most important factors are:

1. Type of steel (e.g. wire, strand, etc.)
2. Diameter of the steel
3. Steel stress level
4. Surface condition of the steel
5. Concrete strength
6. Type of loading
7. Type of release (e.g. flame cut or slow detensioned)
8. Confinement
9. Time-dependent effects
10. Consolidation and consistency of concrete around steel
11. Cover and spacing

A detailed discussion of each point can be found in papers written by Burdette et. al. [5], Cousins et. al. [6], Hanson [7], Kaar et. al. [8], Mitchell et. al. [9] and Russell et. al. [4].

2.5. Previous Research

There are many experimental programs that have investigated the transfer and development length of prestressing strands. A brief summary of the most recent research programs is presented below.

2.5.1. Russell and Burns - The University of Texas at Austin (1993)

Russell and Burns [4] conducted an extensive experimental testing program concerning the bond of pretensioned strands. The project covered the study of transfer and development length for 0.5-in. and 0.6-in. diameter strands. The variables included in the program were: Number of strands, size of strands, debonding, confining reinforcement and dimension of the cross section.

The average measured transfer length for 0.6-in. strands was 41 inches, and for 0.5-in. strands was 30 inches. Measured transfer lengths were longer in specimens where some strands were contaminated with lubricants. Larger specimens, as well as specimens fabricated with higher concrete strengths, had shorter transfer lengths. Confining reinforcement and spacing of the strands had no apparent effect on transfer length.

For 0.5-in. strands the development length in AASHTO-Type beams was 72 inches and in rectangular beams it was 96 inches. The development length in the rectangular beams was longer than expected due to strand contamination (with oil) prior to casting. For 0.6-in. strands the development length in AASHTO-Type beams was 84 inches and in rectangular beams it was less than 78 inches.

2.5.2. Mitchell, Cook, Tham, and Khan - McGill University (1993)

Mitchell et. al. [9] tested single strand prisms. Concrete strength and diameter of the strands were the main variables considered in this project. All the results indicated a reduction in the transfer length for high strength concretes.

2.5.3. Tawfiq - Florida State University (1995)

Tawfiq [10] performed field and laboratory tests on full-scale AASHTO type II prestressed girders. The diameter of the strands in this test program was 0.5 inches. The transfer length as well as the shear capacity of high performance concrete girders were investigated. The concrete strength and the amount of shear reinforcement were the two variables considered in this project. It was found that the transfer length was inversely proportional to the compressive strength. It seems that the amount of shear reinforcement did not affect the strength of the beams in this project. Most of the test girders failed in bond.

2.5.4. Russell and Paulsgrove - University of Oklahoma (1995)

Russell et. al. [14] tested rectangular beams in flexure to determine the development length of 0.5 inch diameter strands. Three different types of failure were distinguished: Flexural, bond and hybrid. The hybrid type of failure was selected for those specimens that reached their ultimate moment but experienced substantial end slip.

Development length tests were performed in sixteen 6 inch x 12 inch rectangular beams. Because these tests are just a portion of a large experimental project, only preliminary results are available.

2.6. Equations for Transfer and Development Length

2.6.1. ACI 318 and AASHTO Code Equations

The ACI 318-95 [11] and AASHTO [12] codes have very similar requirements for development length of prestressing strands. In both codes there is a provision for a minimum embedment length, which is calculated by a simple equation that only takes into account the size of the strand and the effective stress to which this strand is subjected. The ACI 318 code provisions are as follows:

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

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

where d_b is strand diameter in inches, and f_{ps} and f_{se} are expressed in kips/in^2

12.9.2 - Limiting the investigation to cross sections nearest each end of the member that are required to develop full design strength under specified factored loads shall be permitted.

The equation presented above was developed based on tests performed on normal weight concrete members with a minimum cover of 2 inches from center of strand. This equation can be rewritten as:

$$L_d = \frac{f_{se}}{3} \cdot d_b + (f_{ps} - f_{se}) \cdot d_b$$

where the first term represents the transfer length of the strand and the second term represents the additional flexural length of bond required to develop an increase in strand tension due to external loads applied to the member.

The ACI and the AASHTO codes do not specifically state a transfer length requirement. However, sections 11.4.4 of the ACI Code and 9.20.4 of the AASHTO Specification suggest that when calculating V_{cw} a transfer length of 50 times the strand diameter can be considered. This assumption is just a simplification of the transfer length term of the general equation for development length presented above.

The ACI code defines V_{cw} as the nominal shear strength provided by concrete in the web when diagonal cracking results from excessive principal tensile stress.

2.6.2. Proposed Equations for Transfer and Development Length

Researches have proposed several equations for transfer and development length of prestressing strand. Table 2.1, which was taken from Gross' thesis [13], presents some of them. Most of these equations were developed empirically based on experimental results. It is very difficult to say which is more accurate or which is the best because there are too many variables that affect the transfer and development length of prestressing steel, and none of the equations take into account all of them. There is some indication that there may have been differences in the surface conditions for strands used in these studies, leading to differing transfer and development lengths.

Table 2.1. Transfer and Development Length Equations [13]

Author	Year	Transfer Length	Development Length
ACI 318/ AASHTO[1]	1963	$L_t = \frac{f_{se}}{3} \cdot d_b$ $L_t \approx 50 \cdot d_b$	$L_d = L_t + (f_{ps} - f_{se}) \cdot d_b$
Martin & Scott[2]	1976	$L_t = 80 \cdot d_b$	$f_{ps} \le \frac{L_e}{80 \cdot d_b} \cdot \left(\frac{135}{d_b^{\frac{1}{6}}} + 31 \right) \quad L_e \le 80 \cdot d_b$ $f_{ps} \le \frac{135}{d_b^{\frac{1}{6}}} + \frac{0.39 \cdot L_e}{d_b} \quad L_e > 80 \cdot d_b$
Zia & Mostafa	1977	$L_t = 1.5 \cdot \frac{f_{si}}{f'_{ci}} \cdot d_b - 4.6$	$L_d = L_t + 1.25 \cdot (f_{pu} - f_{se}) \cdot d_b$
Cousins, Johnston & Zia[3]	1990	$L_t = \frac{U'_t \cdot \sqrt{f'_{ci}}}{2 \cdot B} + \frac{f_{si} \cdot A_{strand}}{\pi \cdot d_b \cdot U'_t \cdot \sqrt{f'_{ci}}}$	$L_d = L_t + (f_{ps} - f_{se}) \cdot \left(\frac{\frac{A_{strand}}{\pi \cdot d_b}}{U'_d \cdot \sqrt{f'_c}} \right)$
Russell & Burns[4]	1993	$L_t = \frac{f_{se}}{2} \cdot d_b$	$M_{cr} > L_t \cdot V_u$ Fully Bonded $\frac{L_b + L_t}{Span} \le \frac{1}{2} \cdot \left[1 - \sqrt{1 - \frac{M_{cr}}{M_u}} \right]$ Debonded
Mitchell et. al.[5]	1993	$L_t = \frac{f_{si} \cdot d_b}{3} \cdot \sqrt{\frac{3}{f'_{ci}}}$	$L_d = L_t + (f_{ps} - f_{se}) \cdot d_b \cdot \sqrt{\frac{4.5}{f'_c}}$
Burdette, Deatherage & Chew	1994	$L_t = \frac{f_{si}}{3} \cdot d_b$	$L_d = L_t + 1.50 \cdot (f_{ps} - f_{se}) \cdot d_b$
Buckner (FHWA)	1994	$L_t = \frac{1250 \cdot f_{si} \cdot d_b}{E_c}$ $L_t \approx \frac{f_{si}}{3} \cdot d_b$	$L_d = L_t + \lambda \cdot (f_{ps} - f_{se}) \cdot d_b$ $\lambda = (0.6 + 40 \cdot \varepsilon_{ps})$ or $\left(0.72 + 0.102 \cdot \frac{\beta_1}{\omega_p} \right)$ $(1.0 \le \lambda \le 2.0)$

Note: Notation was changed in some cases to provide consistency between equations.

(1) Second equation for Transfer Length is from shear provisions of ACI 318 Section 11.4.

(2) Martin & Scott's Development Length equations limit f_{ps} as a function of L_e.

(3) B = 300 (psi/in) on average; U'_t and U'_d are functions of strand surface conditions.

(4) Russell & Burns' Development Length equations are based on preventing cracking in the transfer zone.

L_b = Length of debonding for debonded strands.

(5) f'_{ci} and f'_c in kip/in^2.

CHAPTER THREE
TEST PROGRAM

3.1. Introduction and Scope of Tests

The test program consisted of four experimental tests performed on two full scale Texas Type C sections with cast in place slabs. The main goal of the test program was to determine the development length of 0.6-in. diameter prestressing strand at two-in. spacing in the two fully bonded normal strength concrete composite beams. The test setup was different for each of the four tests.

Characteristics of the test specimens:

- 54-ft beam
- 0.6-in. diameter prestressing strands
- Normal strength concrete (f'_c = 7000 psi)
- Fully bonded strands
- Slab cast in place
- Minimum cover and strand spacing (2 in.)

The dimensions of the Type C beams were maintained but the number of strands and shear reinforcement were calculated by Carlos Córdova and Michael Braun in May, 1995. The beams were cast in July, 1995 at Texas Concrete Company in Victoria, Texas. Both beams were shipped to the Phil M. Ferguson

Structural Engineering Laboratory at The University of Texas at Austin in November, 1996. The composite slabs were then cast in place prior to testing for development length.

Measurements of the transfer length of the 0.6-in. diameter strands were taken at the plant after gradual releasing of the prestressing force. The beams were instrumented with gauge points at 2 in. spacing using mechanical strain gauges. At transfer the strain data was obtained to determine the strain profile in the concrete at the center of gravity of the strands. The four ends of the two specimens were instrumented. The strain profile then was used to determine the transfer length of the strands.

This chapter explains the design and fabrication of the test specimens. It also contains information about the instrumentation and test setup for the transfer length measurements and development length tests.

3.2. Specimen Design and Designation

3.2.1. Specimen Design

The Texas Type C beam has the following dimensions (See Figure 3.1):

- Total height: 40.0 in.
- Width of top flange: 14 in.
- Average thickness of top flange: 7.75 in.
- Width of web: 7 in.

- Width of bottom flange: 22 in.
- Average thickness of bottom flange: 10.75 in.

There are four rows of strands, two in the bottom flange and two in the top flange. The rows were designated as A, B, C and D. Row A is the very bottom row (bottom flange) and row D is the very top row (top flange) as shown in Figure 3.1. Table 3.1 gives the number of strands per row.

Table 3.1. Position of the Strands

Row Designation	# of strands per row
A	10
B	6
C	2
D	2

The four top strands in rows C and D were added in order to reduce the high tensile stresses that are developed at the top of each end during transfer of the prestressing force.

The beams were designed to ensure that the strain in the prestressing steel at flexural failure was at least the guaranteed minimum elongation of the strand (3.5%).

Enough shear reinforcement was provided to avoid shear failure. Two Grade 60 U-shaped #4 bars at 4 in. were used at both ends for a distance of 12 ft. Then one Grade 60 U-shaped #4 bar at 4 in. was used for the rest of the beam. Additional reinforcement (confinement steel), as shown in Figure A.1, was placed in the anchorage zones to resist splitting stresses due to the transfer of the prestress force. All the strands were fully bonded along the length of each beam. The contractor's drawings for the test beams may be found in Appendix A.

Each beam was designed for two tests. A fixed support was placed at midspan. The fixed support divided the 54 ft beam in two equal spans. The length of the beam was determined based on possible embedment lengths for each side. The 27 ft span allowed a maximum embedment length to be tested of 13 ft causing insignificant damage to the other span. These four totally independent tests for development length were obtained from the two normal strength concrete beams fabricated for this project.

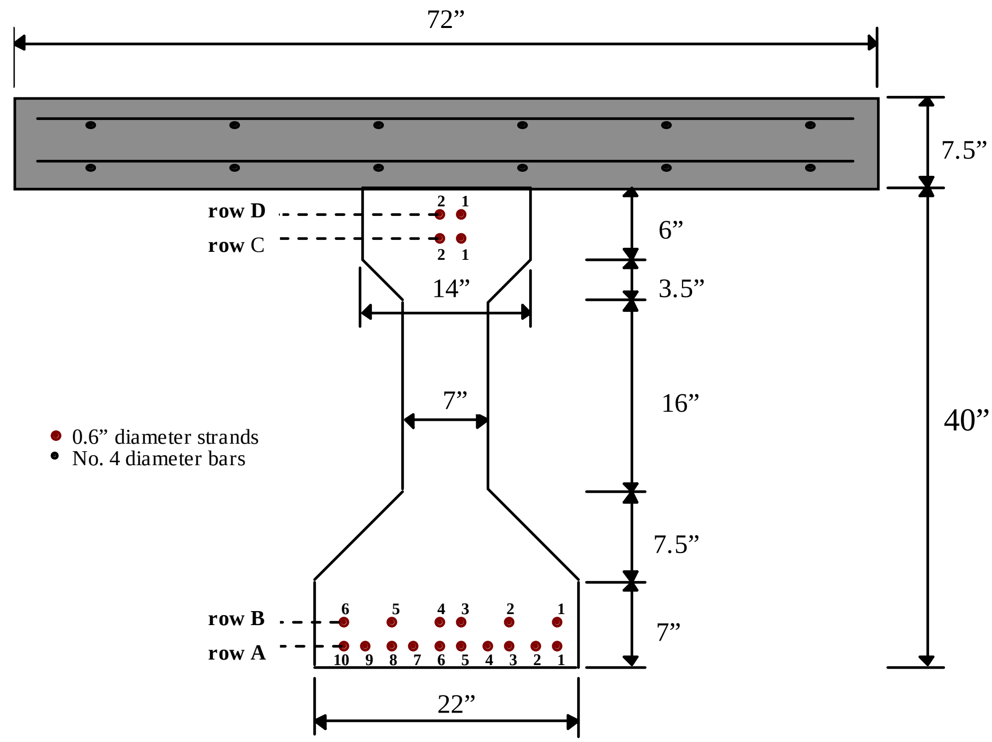


Figure 3.1. Specimen Cross Section (South End)

3.2.2. Specimen and Test Designation

The two specimens were designated as NSC-1 (Normal Strength Concrete 1) and NSC-2 (Normal Strength Concrete 2) at casting. Each end was designated based on its orientation in the place they were cast e.g. NSC-1-NE refers to the north-east side of the first beam. Table 3.2 shows the experimental test designations.

Table 3.2. Experimental Test Designations

Test Designation	Test Number	Beam End	Embedment Length (in)
1-NSC-1-S-120	1	NSC-1-S	120
2-NSC-1-N-93	2	NSC-1-N	93
3-NSC-2-S-78	3	NSC-2-S	78
4-NSC-2-N-72	4	NSC-2-N	72

3.3. Material Properties

3.3.1. Pretensioning Strands

The 0.6-in. diameter Grade 270 low-relaxation seven-wire strand was used as pretensioning reinforcement in the test specimens. The nominal cross-sectional area is 0.217 square inches, which is 41.8 % larger than the 0.153 square inches nominal area of the 0.5-in. diameter strand. The nominal diameter of the 0.6-in. strand is only 20 % larger than the nominal diameter of the 0.5-in. strand. Therefore the increased load capacity of the 0.6-in. strand results in higher bond stresses per unit length of strand. These higher bond stresses may produce anchorage slip and/or splitting cracks parallel to the strand.

The strands used in this study were manufactured by Shinko Wire America Inc. (SWAI). Five tensile tests were performed, one by the manufacturer and four by the researchers of this project. The results of all the tests are summarized in Table 3.3. The load - elongation plots for each test can be found in Appendix B. The strand surface prior to casting was “bright” with no trace of rusting. This condition is probably the most unfavorable for transfer and development lengths.

Table 3.3. Tensile Tests on Prestressing Strands

Test	Ultimate Load (lb)	Ultimate Stress (ksi)	Load at 1% strain (lb)	Stress at 1% strain (ksi)	# of wires broken	Ultimate strain (%)
1	59800	275.6	53900	248.4	6	8.5
2	59300	273.3	53700	247.5	2	8.7
3	59550	274.4	52000	239.6	3	8.1
4	58300	268.7	52750	243.1	3	8.2
Avg.	59238	273.0	53088	244.6	3.5	8.4
SWAI	60600	279.3	56500	260.4	---	9.2

3.3.2. Concrete

The concrete used for the two beams was batched and mixed on-site at the prestressing plant in Victoria, Texas. The design concrete strength at release and at 28 days was 4000 psi and 7000 psi, respectively. A set of 4x8 inch cylinders was cast from a concrete batch corresponding to each beam. The cylinders were cured under the same conditions as the beams and tested in compression at different ages. Plots of compressive strength versus time can be found in Appendix B.

The concrete used for the two slabs was batched and mixed at Capitol Aggregates in Austin, Texas and shipped to the Ferguson Laboratory. The design concrete strength at 28 days was 6000 psi. Two sets of cylinders (4x8 in. and 6x12 in.) were cast from the concrete corresponding to each slab. The cylinders were cured under the same conditions as the slabs and tested in compression at different ages.

Table 3.4. Concrete Mix Design for Beams

Material	Quantity / yd^3 of concrete
Type II cement	452 lb
Fly Ash (Type F)	122 lb
Water	202 lb
Coarse Aggregate (3/4" Rock)	1885 lb
Fine Aggregate (Sand)	1264 lb
Retardant	5.7 oz
Air-entrainment	4.59 oz
High-range water-reducer	69.0 oz
Pollyheed	34.4 oz

Table 3.5. Concrete Mix Design for Slabs

Material	Quantity / yd^3 of concrete
Type II cement	517 lb
Water	250 lb
Coarse Aggregate (3/4” Rock)	1869 lb
Fine Aggregate (Sand)	1355 lb
Retardant	20.7 oz

Tables 3.6 and 3.7 give values of concrete strength at different stages for both beams and slabs. Some values were estimated using a linear interpolation between known (measured) values. Plots of compressive strength versus time are located in Appendix B (Figures B.5 - B.7).

Table 3.6. Concrete Strength for the First Specimen

Specific Time	NSC-1-Beam	NSC-1-Slab	
	4” cylinder	4” cylinder	6” cylinder
At transfer	4360 (1)	-----	-----
First Test	7180 (2)	7000 (1)	7008 (2)
Second Test	7194 (2)	6975 (2)	7045 (2)

(1) Measured value

(2) Estimated value

Table 3.7. Concrete Strength for the Second Specimen

Specific Time	NSC-2-Beam	NSC-2-Slab	
	4" cylinder	4" cylinder	6" cylinder
At transfer	4360 (1)	-----	-----
Third Test	7208 (2)	6517 (2)	6532 (2)
Fourth Test	7222 (1)	6770 (1)	6655 (1)
(1) Measured value (2) Estimated value			

3.4. Fabrication of Beams

The beams were fabricated on July 11 and 12, 1995 at Texas Concrete Company in Victoria, Texas. During the first day and part of the second day the strands were pretensioned and placement of the mild reinforcement took place. In the afternoon of the second day, formwork was erected and both beams were cast in place. The next day the formwork was removed and the strands were released.

3.4.1. Pretensioning Procedure

Each strand was cut at an approximate length, then placed in the bed and anchored at the dead end (North end) using individual chucks. At the live end (South end) a hydraulic jack was used for pretensioning the strands (one by one) to an initial stress of 202.5 ksi (0.75 f_{pu}).

Figure 3.2. Prestressing Bed

3.4.2. Mild Steel Placement

Placement of the stirrups began after the last strand was pretensioned. All of the pieces of reinforcement for stirrups and other unstressed bars (Fig. 3.3) were securely tied to prevent movement when concrete was placed.

Figure 3.3. Mild Steel Reinforcement

3.4.3. Formwork

The contractor used steel forms in the fabrication of the beams. Before the forms were placed in position, dust was removed from the bed using compressed air (Fig. 3.4). The steel forms and the bottom of the bed were lubricated with oil (Fig. 3.5). Transverse steel pieces were used every few feet to maintain the separation and increase the rigidity of the forms. For the ends, the contractor used pieces of plywood as forms.

Figure 3.4. Cleaning of the Bed

Figure 3.5. Oiling of the Bottom of the Bed

Figure 3.6. Formwork

3.4.4. Placement and Curing of Concrete

Concrete was mixed at the on-site batching plant and transported in buckets to the prestressing bed. A crane lifted the bucket over the beam and the concrete was poured inside the forms (Fig. 3.7). Small vibrators attached to the sides of the forms were able to move along the forms vibrating the concrete. Interior vibrators were also used to consolidate the concrete.

The concrete was cast in the afternoon on July 11, 1995. The weather was hot and dry, with an approximate temperature of 100 °F. Because of the intensive heat, temporary shelters were held over the beams by cranes during the casting operation. After casting was completed, the beams were covered first with burlap and then with heavy cotton blankets completely soaked with water to aid in curing the concrete.

Figure 3.7. Placement of Concrete

Figure 3.8. Lifting of Formwork

3.4.5. Release of Prestress Force

The day after casting (July 12, 1995), concrete cylinders were tested to insure that the compressive strength at transfer was met. Then the formwork was removed and initial measurements were taken for transfer length on both ends of the beams. Section 3.5 explains in detail the procedure used for measuring transfer length.

After the initial readings for transfer length were taken, the release of the prestress force began. The contractor slowly decreased the tension in the strands. Once the total force was transmitted, the strands were flame-cut at a point approximately 18 inches from the ends of each beam (Fig. 3.9).

Figure 3.9. Cutting of Strands after Release

3.5. Transfer Length Measurements

Transfer length measurements were performed by measuring strains, at the center of gravity of the bottom strands, on the outside surface of the concrete along the end region of each beam. The concrete strains were measured and plotted with respect to distance from the end of the beam. From the resulting profile, the transfer length was determined.

3.5.1. Instrumentation for transfer length measurements

Concrete strains were measured with detachable mechanical strain gauges (DEMEC gauges). In order to use these gauges, it is necessary first to install

DEMEC points. The DEMEC points are stainless steel discs with a machined hole in the center. The DEMEC points were glued along the side faces of the end regions of the test beams using epoxy. Points were placed at two-inch (50 mm) spacing along the center of gravity of the bottom strands. The DEMEC gauge was used to precisely measure the distance between two DEMEC points approximately 8 in. (20 mm) apart (See Fig. 3.10). Initial (before transfer) and final (after transfer) measurements were taken for each set of points. To ensure an accurate measurement each distance was taken twice. If the readings were not within two gauge divisions (16 microstrains), a third one was taken. All readings were recorded manually on a data sheet and then transferred to a computer. To get the strain profile for each end of the beams, the difference between the initial and final readings was plotted with respect to length along each end side (east and west) of the beam. East and west plots were averaged to get just one plot for each end of the beam (See Figures 4.1 - 4.4).

Figure 3.10. Reading of DEMEC Points

Figure 3.11. End Slip Measurements at Transfer

3.5.2. End Slip Measurements

End slip measurements were taken at both ends of the beams. Small clamps were attached to each strand and the distance from the clamp to the face of the beam was recorded using a micrometer with an accuracy of 0.0004 in. (See Fig. 3.11). Measurements were taken before and after the prestressing force was released. The difference between the two lengths gives the end slip.

3.6. Development Length Measurements

Tests for measuring the development length were performed in February, 1996 at the Ferguson Structural Engineering Laboratory at The University of Texas at Austin. The development length cannot be measured directly. It requires that the embedment length be varied from test to test. An initial embedment length is chosen for the first test, then based on the results of this test the embedment length for the second test is selected. The same procedure is used for subsequent tests. Failure mode is the parameter that determines where to go for the next test e.g. if flexural failure occurs in the first test, then the embedment length is reduced. On the contrary, if bond failure occurs in the first test, then the embedment length is increased. Following this procedure the development length can be estimated.

3.6.1. Test Setup

The test setup for each specimen included a simply supported beam with its cantilever. Each beam was placed first on two reinforced concrete pedestals (one at each end). A third pedestal was used to divide the 54-foot long beam in two equal spans. Neoprene pads with steel reinforcement were placed on each pedestal as bearing pads. The load was applied on top of a spreader beam which was placed at the designed position along the 27-foot simple span. A 1000 kip ram was used to provide a point load on the spreader beam as shown in Figures 3.14 and 3.15. The ram was moved for every test to a new position along the spreader beam to create a constant moment region in the prestressed concrete beam (between the load points). The only parameter that varied for each test was the embedment length.

Table 3.8. Development Length Test Setup Parameters

Test Designation	Supported span (ft)	Cantilever Length (ft)	Constant Applied Moment Region (ft)	Embedment Length (in)
NSC-1-S-120	27	27	4	120
NSC-1-N-93	27	27	4	93
NSC-2-S-78	27	27	4	78
NSC-2-N-72	27	27	4	72

3.6.2. Instrumentation for development length measurements

Each test was instrumented to measure the applied load, the beam deflection, strand end slip and concrete strains. An electronic load cell was placed between the spreader beam and the ram to measure the load. Deflection under the beam (Fig. 3.12) and end slip (Fig. 3.16 and 3.17) were measured by linear potentiometers. Concrete strains were measured on top of the concrete slab in the constant moment region of each test. Figure 3.15 shows the location of the electronic resistance strain gauges on top of the slab. Two pair of DEMEC points were also installed as a back-up system. During the tests, the concrete strain was checked periodically to be sure that it was below 0.003.

Figure 3.12. Linear Potentiometers under the Beam

Figure 3.13. Test Setup for Development Length Measurements

Figure 3.14. Typical Development Length Test

Figure 3.13 and 3.14 show a typical loading condition. The embedment length was varied from test to test while the span was kept constant for all tests. A distance of 48 in. between the load points of the spreader beam was selected and it was kept constant for all tests. All of the electronic equipment and instruments were tested and calibrated in advance.

Figure 3.15. Location of Strain Gauges on Top of the Beam

Figure 3.16. End Slip Instrumentation (Bottom Flange)

3.6.3. End Slip Measurements

Linear potentiometers were used for end slip measurements. A linear potentiometer was attached to each strand. Because the potentiometers need to bear on a smooth surface in order to get accurate measurements, long rectangular plastic plates were glued to the concrete surface (Fig. 3.16 and Fig. 3.17). Each linear potentiometer was connected to the data acquisition system. Readings were recorded at each load interval.

Figure 3.17. End Slip Instrumentation

3.6.4. Test Procedure

Before any load was applied to the specimen, all the electronic gauges were calibrated by inserting a block of known thickness. Following calibration of the electronic gauges, the computer was reset, so all the readings were set to zero. Initial readings were also taken for the dial gauges and DEMEC points.

Load was applied in increments of 40 kips until the formation of the first flexural or shear crack. After first cracking, the increment was reduced to 20 kips until the loss of the member's stiffness was evident. From this point up to failure, the load was applied in deflection increments. The load versus displacement was recorded on a plotter (Figure 3.18).

Figure 3.18. Load vs. Displacement

Readings of all the instruments were taken at every increment of load. Flexural and shear cracks were also marked at every stage. The test continued until a flexural or bond failure occurred. Flexural failure was accepted to have taken place when the strand strain was at least 3.5%. This strain indicates a very ductile behavior. Bond failure would take place when large end slip of one or more strands happened with a significant loss of the beam capacity. It was desired not to destroy the beams because of safety reasons and to minimize the damage when testing was performed for the other span.

After the beam had failed, the load was removed in three or four steps. All readings were taken at each stage. All the data was stored onto a floppy disk for later reduction.

CHAPTER FOUR
TEST RESULTS

4.1. Introduction

Results of end slip, transfer length and development length measurements are presented in this chapter. A brief explanation of the method used for data reduction is also described. The results presented in this chapter are graphs. All the data is located in Appendices D and E.

4.2. Transfer Length Measurements

4.2.1. Method of Data Reduction

Strain measurements were taken with the DEMEC strain gauge at each face of the four beam ends. The procedure used was described in Section 3.5.1. All the data was first recorded on paper and then transferred to a computer spreadsheet. The data was then manipulated using the procedure described in this section.

First, two readings were taken for each set of points. The average was calculated for the initial (before transfer) and final (after transfer) readings. The difference between the two averages was multiplied by the gauge factor of 8.0 to get a differential strain. This differential strain is the average strain between the two DEMEC points when the prestress force is transferred. The same procedure was followed for all the readings at each face. Then, the differential strains of the east face were averaged with the differential strains of the west face at each end. These final values were then smoothed to reduce the variability in the data. The technique used for smoothing consists of taking the average over three gauge lengths.

$$\text{Strain}_n = \frac{\text{Strain}_{n-1} + \text{Strain}_n + \text{Strain}_{n+1}}{3}$$

4.2.2. Measured Strains at Transfer

The smoothed strain profiles at transfer for all four beam ends are shown in Figures 4.1, 4.2, 4.3 and 4.4. Data for these figures is given in Appendix D. After the force was transferred two readings were taken at different times. The first reading was taken immediately after transfer, while the second reading was taken after six months. It can be seen that in all cases the shape of the curve remained the same, however all curves moved upwards due to creep and shrinkage strains in the concrete.

The theoretical strain profile is a straight line that goes from zero at the beginning of bond (end of the member in this case) to a maximum value at the end of the transfer zone, followed by an approximately horizontal line. It would be a perfect horizontal line if the beam were weightless.

All the specimens showed a linear increase in the transfer zone, followed by a smooth plateau. The south end of the second beam (Figure 4.4) seems to have two plateaus. It was initially thought that contamination of strands with oil during the fabrication process could have caused this unusual behavior. This theory was discarded after the development test performed at that end showed insignificant end slip for most of the strands. Therefore the second plateau is probably a mistake in the initial transfer length measurements.

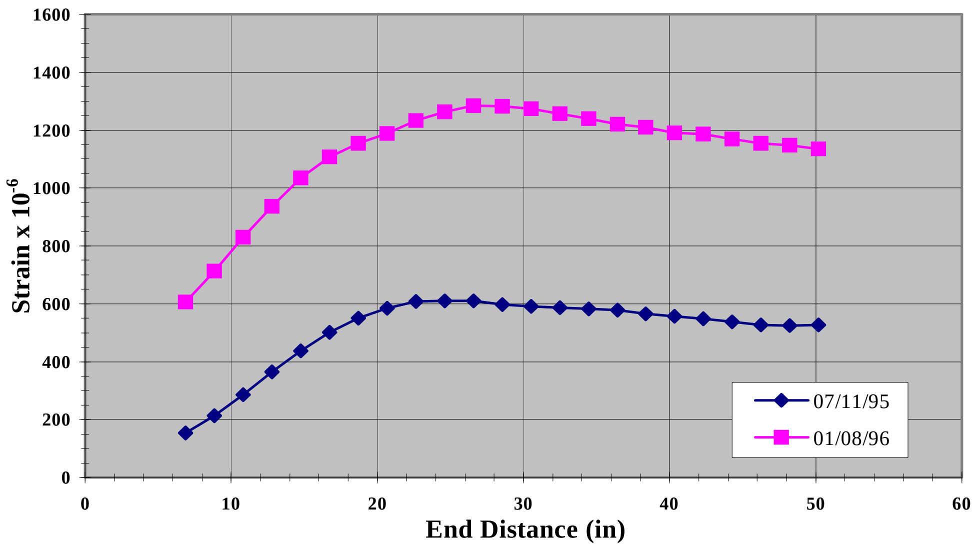


Figure 4.1. Smooth Strain Profile for South end of NSC-1 Beam

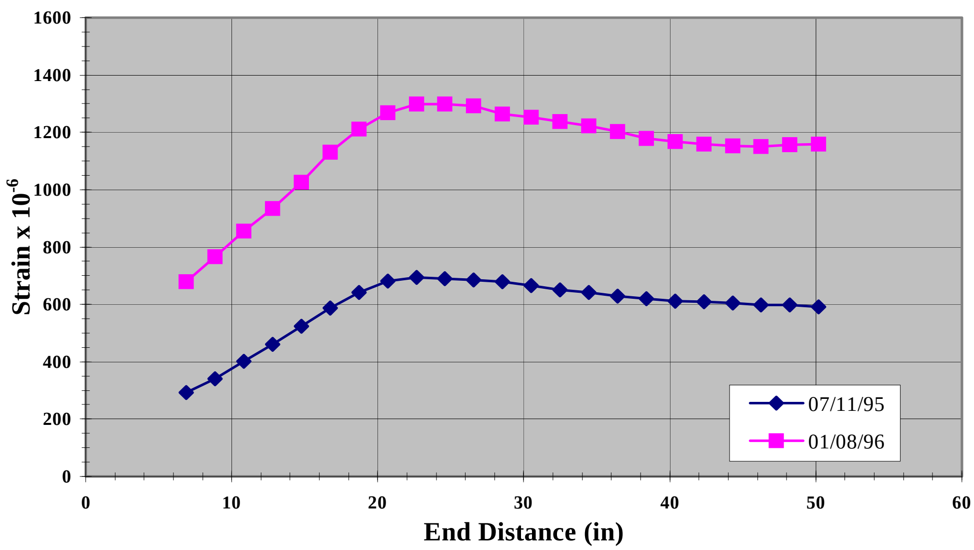


Figure 4.2. Smooth Strain Profile for North end of NSC-1 Beam

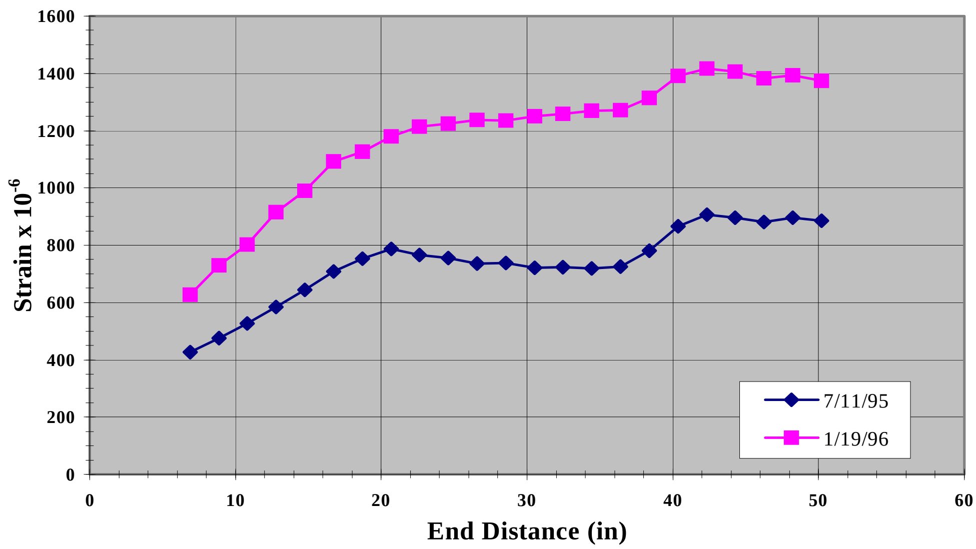


Figure 4.3. Smooth Strain Profile for South end of NSC-2 Beam

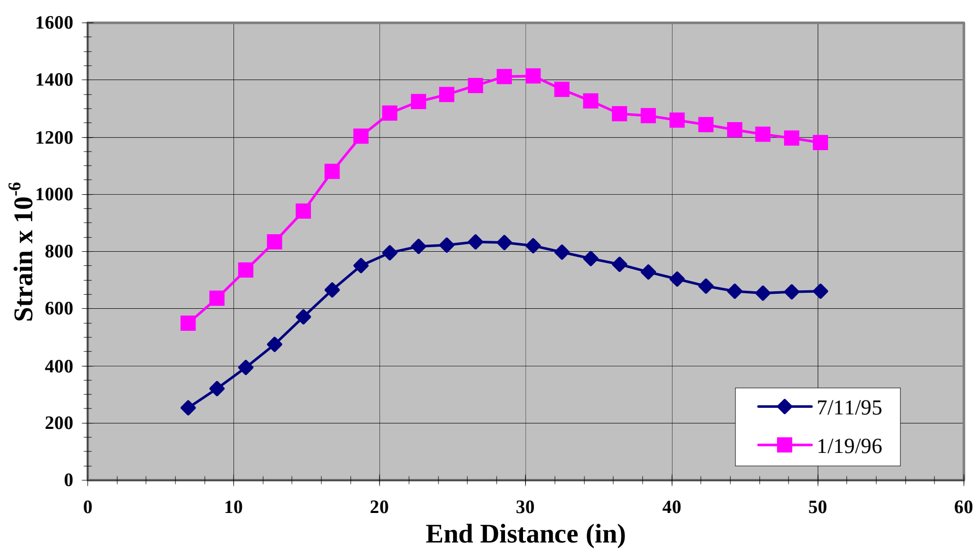


Figure 4.4. Smooth Strain Profile for North end of NSC-2 Beam

The first plateau of Figure 4.3 is reached at about 21 in. end distance, which is very nearly the same as the data in Figure 4.4 for the other end of the same beam. This indicates that the transfer is complete at the distance of 21 inches in Figure 4.3 and the variation in data for end distance greater than about 35 inches in Figures 4.3 and 4.4 have no significance with respect to the transfer length

4.2.3. Measured End Slip at Transfer

End slip measurements were taken at the four ends of the two beams following the procedure described in Section 3.6. Measured end slips are shown in Figures 4.5, 4.6, 4.7 and 4.8. Data for these figures is given in Table D.5 located in Appendix D.

Table 4.1 summarizes the average end slip for each end. It can be seen that the strands in the second beam experienced larger average end slips than the strands in the first beam.

Table 4.1. Average End Slips

Beam End	Avg. End Slip (in)
NSC-1-South	0.0709
NSC-1-North	0.0685
NSC-2-South	0.0787

NSC-2-North	0.0799

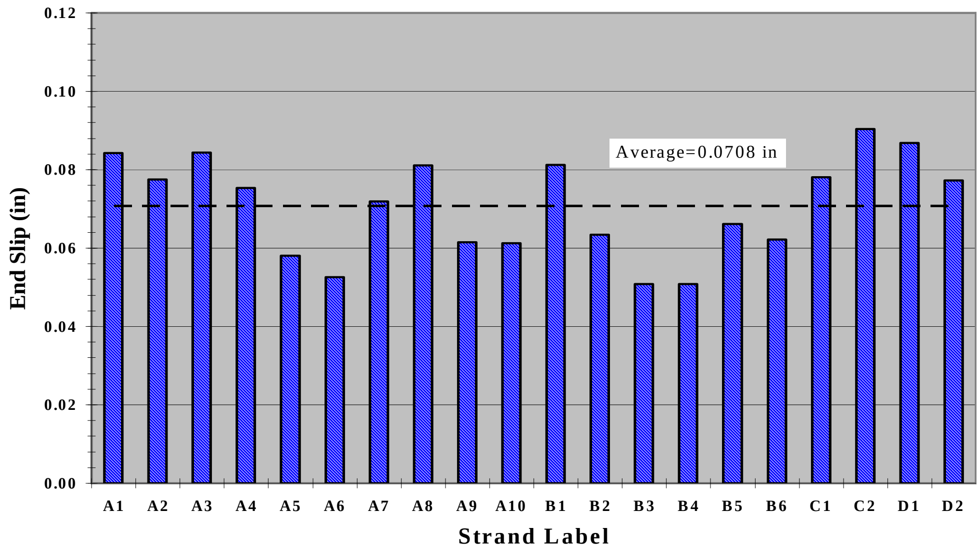


Figure 4.5. Measured End Slips at Transfer for NSC-1-South End

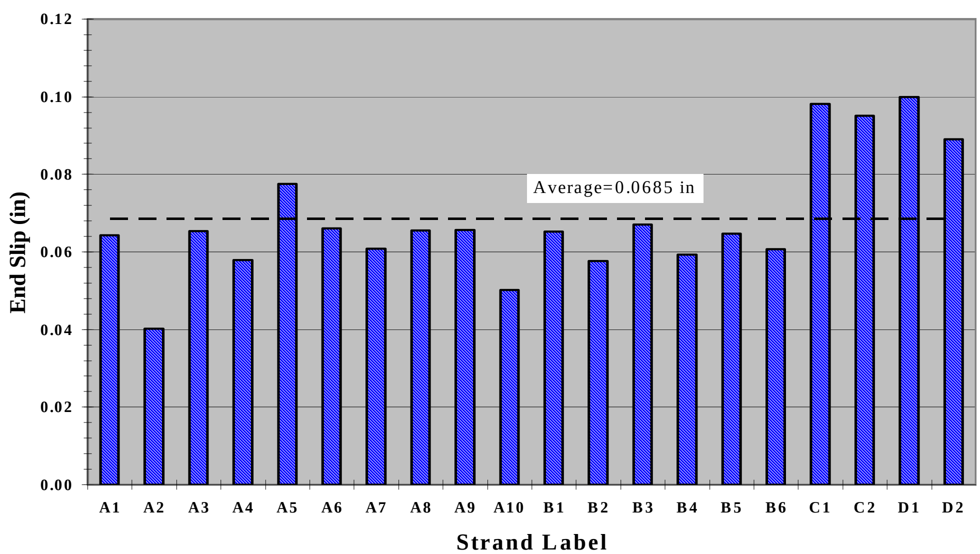


Figure 4.6. Measured End Slips at Transfer for NSC-1-North End

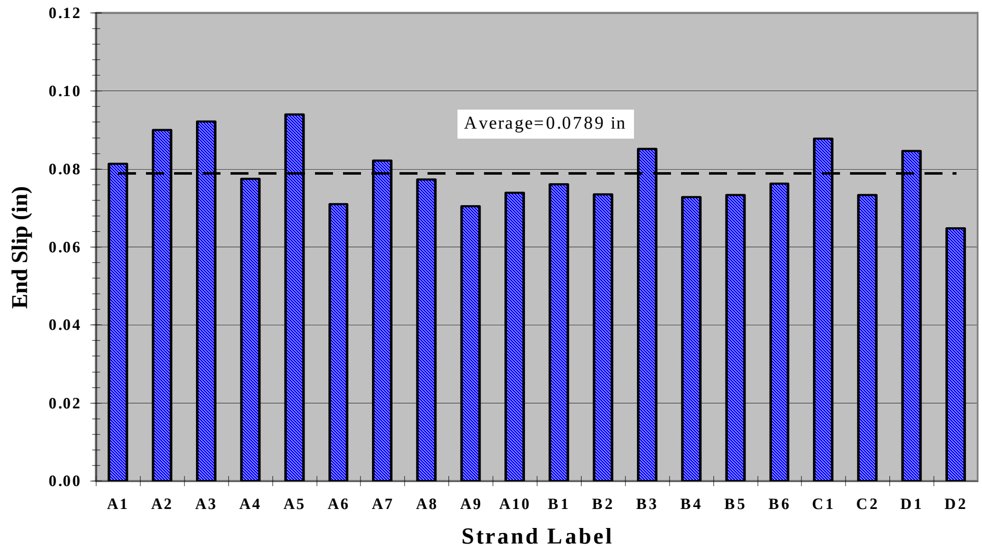


Figure 4.7. Measured End Slips at Transfer for NSC-2-South End

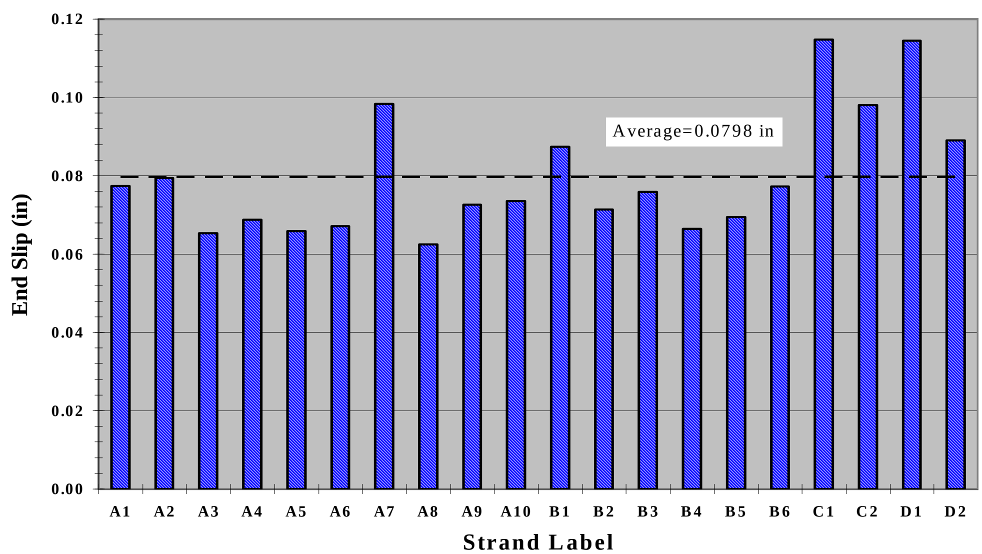


Figure 4.8. Measured End Slips at Transfer for NSC-2-North End

4.3. Development Length Test Results

4.3.1. Introduction

The results of the four development length tests performed on the two beams are presented in this section. As stated before, only straight fully bonded strands were used in these beams.

The failure type can be classified as either flexural or bond failure. In order to classify a failure as a flexural failure two criterias are considered. First, the ultimate flexural capacity of the cross section should be achieved; and second, the beam should present a ductile behavior. A failure is classified as a bond failure when there is a sudden loss of the beam's capacity with significant measured end slips.

A third type of failure was encountered in the last test. This failure can be classified as a compression strut failure. In this last test, the embedment length was only one and a half times the height of the specimen. Because of the short embedment length used, the contribution of the arch effect on the beam's strength was significant.

The maximum applied load for each test is reported. This load does not include the self-weight of the beam or the weight of the spreader beam. The maximum net deflection and the residual net deflection for each test are also reported. Net deflection is defined as the measured maximum deflection minus the measured bearing compression. The residual net deflection is the permanent deflection of the beam after the specimen is completely unloaded. For each test a plot of load versus deflection is presented.

Based on the maximum applied load and the position of the loading points along the beam, the maximum moment at the critical section is calculated for each test. The critical section in each test is located under the load that is closest to a support.

The maximum compressive strain at the top fiber is reported. Eight electronic resistance strain gauges were used to measure strains in the concrete. Three groups of two, four and two gauges were placed near the north load point, at midway between load points and near the south load point, respectively (See Fig. 3.15). The maximum single reading and the maximum average between east and west side measurements are reported.

An approximate maximum strand elongation for row A is reported for each test. The elongation is calculated assuming that changes in strain in the concrete are the same in the steel and that the strain distribution is linear over the depth of the beam.

End slips were recorded for each strand using the procedure indicated in Section 3.7.3.

Pictures of the two beams were taken during and after the tests were completed. East and west sides of each beam end were photographed. These pictures are presented in this chapter for each test. Flexural and shear cracks were recorded at each load step. The loads that produced the first flexural and shear cracks were also recorded. Several cracks, at both faces of the beam, were monitored during each test. Every other interval of load the crack widths were recorded for those selected cracks. In this chapter only the maximum crack width for each test is presented.

All the data for the four development tests, which includes deflection measurements, concrete strain measurements and end slip measurements, are presented in a tabular form in Appendix E.

4.3.2. Test 1-NSC-1-South -120

An embedment length of 120 inches was selected for this first test. The constant moment region was 48 inches and the length of the simple span was 26.83 feet. The failure of this specimen was clearly classified as flexural in accordance with the criteria explained in the previous section.

Figure 4.9 shows a plot of applied load versus net deflection. The first flexural and shear cracks appeared at a load of 460 kips with a corresponding net deflection of 0.22 inches. The specimen started losing its stiffness after a load of 470 kips. The maximum applied load was 674 kips with a maximum net deflection of 2.44 inches. The corresponding maximum moment at the critical section was 3680 kip-ft. The unloded specimen displayed a permanent net deflection of 0.69 inches.

The maximum crack width at ultimate load was 0.13 inches. This crack was located on the west side, within the constant moment region, at a distance of approximately 11.5 feet from the south end of the beam.

The electronic resistance strain gauge that measured the maximum compressive strain of 0.00292 was located midway between the two load points. A maximum average compressive strain of 0.00286 was recorded for the two gauges located near the north load point.

The first crack in the slab became visible at a load of 645 kips. Several cracks reached the slab at ultimate load. The average depth of the neutral axis measured from the top fiber of the slab was 3.81 inches.

The approximate strand elongation, based on the maximum average compressive strain and the average depth of the neutral axis, was 3.7 %. This elongation was calculated replacing the strands of the bottom flange with an equivalent strand located at their center of gravity. The equivalent strand is located at 2.75 inches from the bottom face of the beam.

No significant end slip was recorded for any of the twenty strands at any point during the test. Maximum end slips for rows C and D were 0.00004 and 0.00003 inches, respectively. An end slip of 0.00601 inches was the maximum end slip recorded for row A. Among all strands, B1 had the maximum measured end slip of 0.00626 inches.

Crack patterns for the east and west faces of the specimen can be seen in Figures 4.10 and 4.11 respectively. Cracking was well distributed in and around the constant applied moment region. Only one shear crack extended to the bottom flange. This crack passed through the transfer zone of the strands in row B and stopped just after crossing it. This crack did not reach the bottom face of the beam and it seemed to have no significant effect on the development of the prestressing strands.

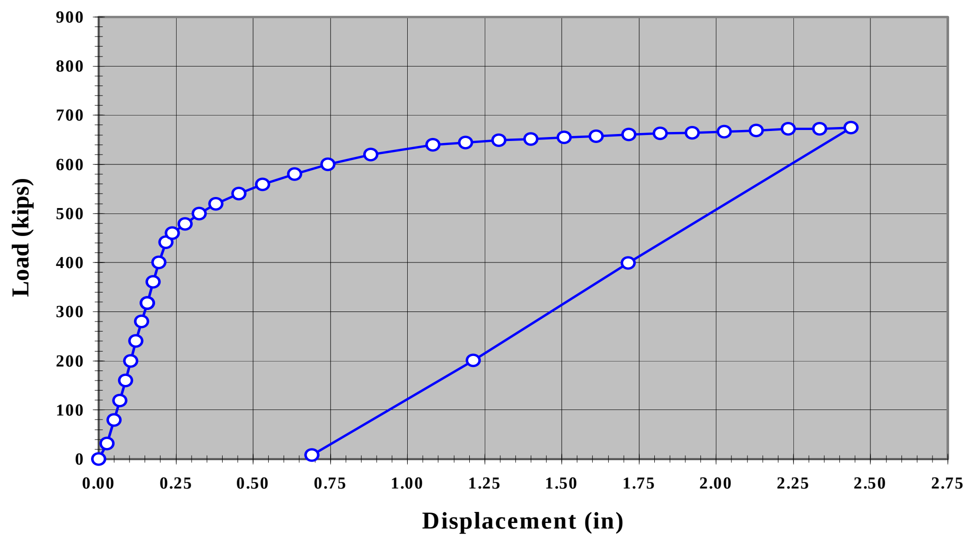


Figure 4.9. Load vs. Deflection for Test 1-NSC-1-South-120

Figure 4.10. Cracking Pattern for Test 1-NSC-1-SE-120

Figure 4.11. Cracking Pattern for Test 1-NSC-1-SW-120

4.3.3. Test 2-NSC-1-North -93

Based on the results of the first test, an embedment length of 93 inches was selected for this second test. The constant moment region and the length of the simple span were not changed. The failure of this specimen was also classified as flexural in accordance with the criteria explained in Section 4.3.1.

Figure 4.12 shows a plot of applied load versus net deflection. The first flexural and shear cracks appeared simultaneously at a load of 545 kips. The corresponding net deflection was 0.30 inches. The specimen started losing its stiffness when it cracked. The maximum applied load was 757 kips with a maximum net deflection of 2.42 inches. The corresponding maximum moment at the critical section was 3690 kip-ft. The unloded specimen displayed a permanent net deflection of 0.74 inches.

The maximum crack width at ultimate load was 0.15 inches. This crack was located on the east side, within the constant moment region, at a distance of approximately 9.5 feet from the north end of the beam.

The electronic resistance strain gauge that measured the maximum compressive strain of 0.00263 was located near the south load point. A maximum average compressive strain of 0.00254 was recorded for the two gauges located near the north load point.

The first crack in the slab became visible at a load of 706 kips. Several of the flexural cracks extended into the slab at ultimate load. The average depth of the neutral axis measured from the top fiber of the slab was 3.63 inches.

The approximate strand elongation, based on the maximum average compressive strain and the average depth of the neutral axis, was 3.5 %. This elongation was calculated replacing the strands of the bottom flange with an equivalent strand located at their center of gravity. The equivalent strand is located at 2.75 inches from the bottom face of the beam.

Although the measurements indicated an increase in the end slip of the twenty strands, they were still insignificant. Top strands in rows D and C registered movements up to 0.00142 and 0.00214 inches respectively. Measurements indicated that strands in row B experienced the most end slip. End slips of 0.01416 inches and less were measured for row A. Strand B3 had the maximum end slip of 0.02269 inches.

Crack patterns for the east and west faces of the specimen can be seen in Figures 4.13 and 4.14, respectively. Cracking was well distributed in and around the constant applied moment region. Several shear cracks extended to the bottom face of the beam. Some crossed the transfer zone of the strands in rows A and B. These cracks seemed to have no effect on the development of the prestressing strands.

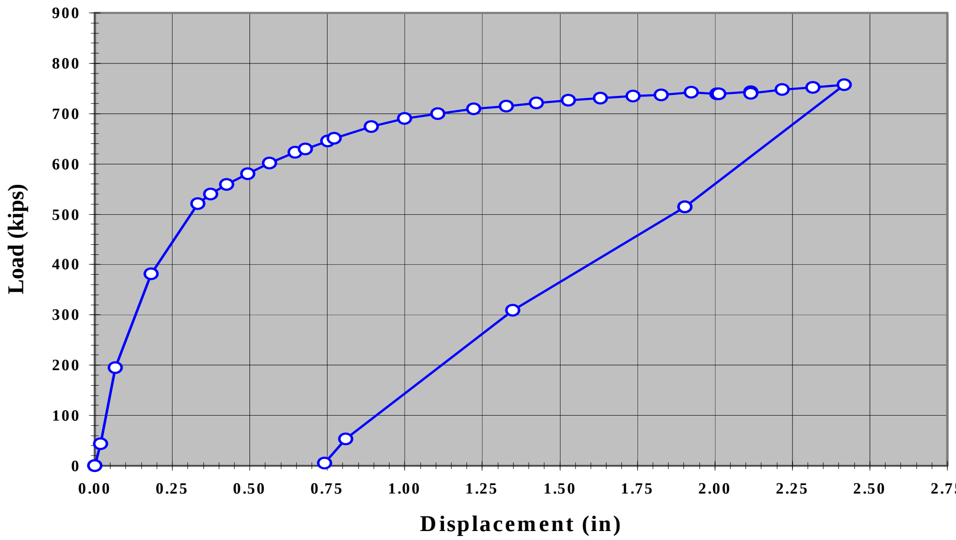


Figure 4.12. Load vs. Deflection for Test 2-NSC-1-North-93

Figure 4.13. Cracking Pattern for Test 2-NSC-1-NE-93

Figure 4.14. Cracking Pattern for Test 2-NSC-1-NW-93

4.3.4. Test 3-NSC-2-South -78

The embedment length for this third test was reduced to 78 inches. The constant moment region and the length of the simple span were maintained. The failure of this specimen was again classified as flexural in accordance with the criteria explained in Section 4.3.1.

Figure 4.15 shows a plot of applied load versus net deflection. In this test, shear cracks formed before flexural cracks. First shear cracks appeared at a load of 458 kips with a corresponding net deflection of 0.16 inches, while the first flexural crack formed at a load of 558 kips with a corresponding net deflection of 0.22 inches. The specimen started losing its stiffness after a load of 560 kips.

The maximum applied load was 841 kips with a maximum net deflection of 2.43 inches. The corresponding maximum moment at the critical section was 3690 kip-ft. Once the beam was completely unloaded, the permanent net deflection was 0.73 inches.

The maximum crack width at ultimate load was 0.15 inches. This crack was located on the west side under the load point that was 6.5 feet from the south end of the beam.

The electronic resistance strain gauge that measured the maximum compressive strain of 0.00273 was located near the south load point. A maximum average compressive strain of 0.00249 was recorded for the two gauges located near the north load point.

The first crack in the slab became visible at a load of 755 kips. As in previous tests, several cracks extended into the slab at the final load. The average depth of the neutral axis measured from the top fiber of the slab was 3.31 inches.

The approximate strand elongation, based on the maximum average compressive strain and the average depth of the neutral axis, was 3.7 %. This elongation was calculated replacing the strands of the bottom flange with an equivalent strand located at their center of gravity. The equivalent strand is located at 2.75 inches from the bottom face of the beam.

Larger end slips were recorded in this test. The maximum end slips for rows D, C, B and A were 0.00200, 0.00009, 0.04970 and 0.02781 inches, respectively. Strand B6 had the maximum end slip of 0.04970 inches.

Crack patterns for the east and west faces of the specimen can be seen in Figures 4.16 and 4.17, respectively. Once again cracking was well distributed in and around the constant applied moment region. Many shear cracks extended to the bottom face of the beam. Several of them crossed the transfer zone of the strands in rows A and B. These cracks seemed to have no effect on the development of the prestressing strands.

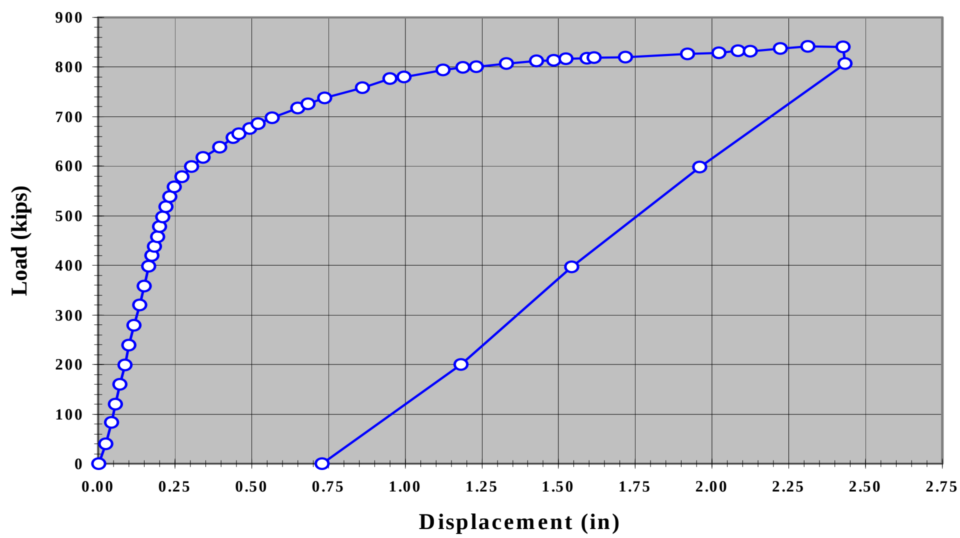


Figure 4.15. Load vs. Deflection for Test 3-NSC-2-South-78

Figure 4.16. Cracking Pattern for Test 3-NSC-2-SE-78

Figure 4.17. Cracking Pattern for Test 3-NSC-2-SW-78

4.3.5. Test 4-NSC-2-North -72

As a last attempt to precipitate a bond failure, an embedment length of 72 inches was selected for this fourth test. The constant moment region and the length of the simple span were maintained. The failure of this specimen was going to be classified as flexural, but one more increment of displacement caused a compression strut failure.

Figure 4.18 shows a plot of applied load versus net deflection. As in the previous test, shear cracks developed before flexural cracks. First shear cracks appeared at a load of 440 kips with a corresponding net deflection of 0.16 inches, while the first flexural crack formed at a load of 560 kips with a corresponding net deflection of 0.21 inches. The specimen started losing its stiffness after a load of 600 kips. The maximum applied load before failure was 871 kips with a maximum net deflection before failure of 1.83 inches. The corresponding maximum moment at the critical section was 3600 kip-ft. A net deflection of 1.01 inches remained on the specimen once the load was completely removed.

The maximum crack width at ultimate load was 0.11 inches. This crack was located on the west side, within the constant moment region, at a distance of approximately 6.5 feet from the north end of the beam.

The strain gauge, near the north load point, measured the maximum compressive strain of 0.00272. A maximum average compressive strain of

0.00242 was recorded for the gauges located near the north load point. Except for those two strain gauges, the remaining gauges recorded strains below 0.002.

The first crack in the slab became visible at a load of 760 kips. By the end of the test, several flexural cracks extended into the slab. The average depth of the neutral axis measured from the top fiber of the slab was 3.44 inches.

The approximate strand elongation, based on the maximum average compressive strain and the average depth of the neutral axis, was 3.6 %. This elongation corresponds to an equivalent strand located at 2.75 inches from the bottom face of the beam.

End slip measurements after failure of the beam are not presented because they do not have any meaning. Before failure, the maximum end slip for rows D, C, B and A were 0.00305, 0.00206, 0.05527 and 0.03615 inches. Strand B3 was the strand that experienced the most end slip before failure.

Crack patterns for the north, east and west faces of the specimen can be seen in Figures 4.19, 4.20 and 4.21 respectively. Cracking was well distributed in and around the constant applied moment region. A great concentration of shear cracks occurred near the north end. Many shear cracks reached the bottom face of the beam, and most crossed the transfer zone of the strands in rows A and B. Although the width and distribution of these cracks could have affected the development of the prestressing strands, no significant effect was noted.

The failure of the specimen was sudden and quite explosive. A load of 871 kips was recorded in two consecutive displacement increments before the beam failed. The failure would have been classified as flexural if the last increment of displacement had not been imposed. Because this was the final test, it was decided to push the beam to its limit to determine if a bond failure could occur. The strands did not experience general slip before the beam failed.

A compressive strut, between the north load point and the bearing pedestal, caused crushing of the concrete. The compressive force crushed the cover of the web concrete causing a sudden loss of the beam's strength. The beam unloaded itself until a new equilibrium position was reached.

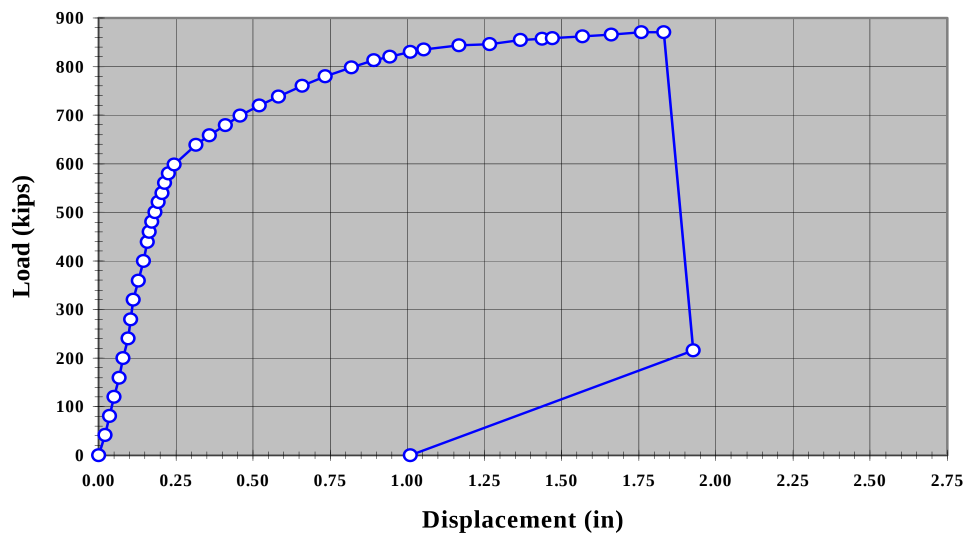


Figure 4.18. Load vs. Deflection for Test 4-NSC-2-North-72

Figure 4.19. North End of Beam after Failure

Figure 4.20. Cracking Pattern for Test 4-NSC-2-NE-72

Figure 4.21. Cracking Pattern for Test 4-NSC-2-NW-72

4.3.6. Summary of Results

The results of the four development tests are summarized in Table 4.2. The first three tests failed in flexure, while the last test failed in a compression strut type failure (See Figures 4.22 and 4.23), following the carrying of a flexural failure moment capacity. The top fiber concrete strain was above 0.0025 for all tests. The average elongation of the bottom strands was above 3.5%. No significant end slip was recorded in any of the tests before failure. Only some strands in the last test suffered large end slips as a consequence of the compression strut failure. The four specimens demonstrated a ductile behavior with cracks well distributed both within and outside the constant moment region.

Table 4.2. Summary of Development Length Test Results

Test	**1-NSC-1-120**	**2-NSC-1-93**	**3-NSC-2-78**	**4-NSC-2-72**
Failure Type	**Flexural**	**Flexural**	**Flexural**	**Comp. strut**
Maximum Applied Load (kips)	674	757	841	871
Moment at Critical Section (kip-ft)	3680	3690	3690	3600
Maximum Net Deflection (in)	2.44	2.42	2.43	1.83
Maximum Top Fiber Strain (in/in)	0.00292	0.00263	0.00273	0.00272
Maximum End Slip Before Failure (in)	0.00626	0.02269	0.04970	0.05527
Approximate Strand Elongation (%)	3.7	3.5	3.7	3.6

Figure 4.22. Compression Strut in Concrete

Figure 4.23. Compression Strut Failure

CHAPTER FIVE
DISCUSSION OF TEST RESULTS

5.1. Introduction

Results of end slip, transfer length and development length tests are analyzed in this chapter. End slip measurements are used for predicting the transfer length of the strands. Results of transfer and development length reported in previous experimental programs are compared to the results obtained in this project. Also, the accuracy of several proposed equations for transfer and development length is investigated. Variables that could have negatively affected the results of this experimental program are briefly discussed.

5.2. Transfer Length Measurements

5.2.1. Determination of Transfer Length

Transfer length for the four beam ends was determined from the smoothed strain profiles presented in Figures 4.1, 4.2, 4.3 and 4.4. There are several methods that can be used for determining the transfer length e.g. the slope-intercept method, the 95% or 100% average maximum strain method, etc.. All of these methods are applicable when the strain profile is well-defined and a fairly uniform strain plateau is present. The results obtained by any of these methods cannot be taken as the “true” transfer length because there is not sufficient research at the moment to confirm their validity. The 95% maximum strain method will give shorter transfer lengths than the 100% maximum strain method. A simple inspection of the strain profile gives as good results as these other methods. For this study, it was decided to use a simple inspection for determining the transfer length in all the tests. Figure 5.1 illustrates the transfer length estimated for the north end of the first beam (NSC-1-North).

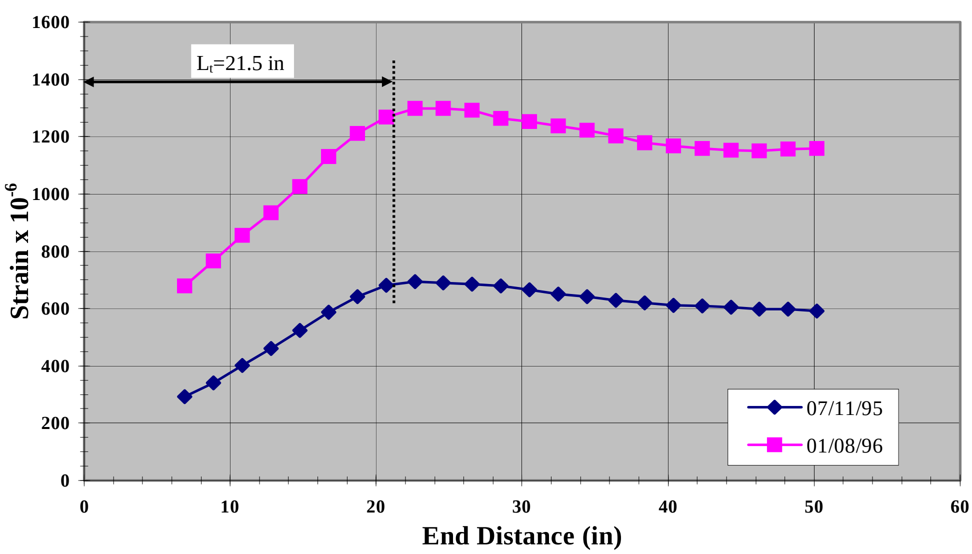


Figure 5.1. Transfer Length

Table 5.1. Estimated Transfer Length

Beam End	Transfer Length (in)

NSC-1-South	22.0
NSC-1-North	21.5
NSC-2-South	20.5
NSC-2-North	22.5
Average	21.6

Table 5.1 presents the estimated transfer length for all the beam ends. The maximum and minimum transfer lengths of 22.5 and 20.5 inches correspond to the north and south ends of the second beam. The average for the four transfer tests was 21.6 inches.

5.2.2. Transfer Length Based on End Slip Measurements

Actual end slip measurements are used to approximate transfer length. Elastic shortening for each strand, from the face of the beam to the attached clamps, is subtracted to get the actual end slip. The following formula [4] is used for transfer length:

$$L_t = \frac{2 \cdot Slip \cdot E_{ps}}{f_{si}}$$

where Slip is the actual end slip, E_{ps} is the elastic modulus of the prestressing strand (28000 ksi) and f_{si} is the stress in the strand after transfer (202.5 ksi), but before prestress losses.

Table 5.2. Transfer Length Based on End Slip Measurements

Beam End	Avg. End Slip (in)	Transfer Length (in)
NSC-1-South	0.07087	19.6
NSC-1-North	0.06850	18.9
NSC-2-South	0.07874	21.8
NSC-2-North	0.07992	22.1
Average	0.07441	20.6

The average transfer length based on the average measured end slip is 5% less than the average transfer length obtained from the smoothed strain profiles. This is to be expected since the actual curves are not exactly the intersection of a straight line with a horizontal plateau (theoretical curve). The slightly smaller transfer lengths in Table 5.2 compare to those in Table 5.1 as expected.

5.2.3. Comparison of Transfer Length with Previous Research

Results of selected previous projects are summarized in Table 5.3. Only the transfer lengths of 0.6 in. diameter strands in normal strength concrete were selected. Burdette et. al. [5] and Cousins et. al. [6] have reported transfer lengths between 21 and 68 inches. These results bracket the average transfer length of 22.6 inches obtained in this study. Russell and Burns [4] reported transfer lengths between 32 and 46 inches.

Table 5.3. Transfer Lengths from Previous Research

Researchers	f'_{ci} (psi)	Transfer Length (in)
Kaar et. al. (1963) [8]	1660 - 5000	28 - 52
Cousins et. al. (1990) [6]	4740 - 4750 4190 - 4740	44 - 68 (1) 22 - 39 (2)
Lane (1992) [14]	4330	43 (1) 26 (2)
Russell & Burns (1993) [4]	3850 - 4790	32 - 46
Burdette et. al. (1994) [5]	4100 - 5450	21 - 30
(1) Uncoated strands (2) Epoxy coated strands with grit		

The strand condition, which can affect significantly the transfer length of prestressing strands, was not clearly specified in all of the previous studies. In this research study, the surface condition of the strands was clean with no rust.

5.2.4. Comparison with Equations for Transfer Length

Several equations from Table 2.1 were used for estimating the transfer length of the 0.6-in diameter strands. The values found are reported in Table 5.4. The minimum calculated transfer length was 34.2 inches and the maximum was 52.8 inches. The ACI 318/AASHTO equation predicted a transfer length of 35.2 inches which is 56% longer than the average transfer length measured in this study.

Table 5.4. Transfer Lengths from Selected Equations

Equation	Transfer Length (in)
ACI 318 / AASHTO [11,12]	35.2
Martin & Scott [15]	48.0
Zia & Mostafa [17]	38.3
Cousins, Johnston & Zia [16]	54.4 (1)
Russell & Burns [4]	52.8
Mitchell et. al. [9]	34.2
Burdette, Deatherage & Chew [5]	41.0
Buckner (FHWA) [19]	38.4 (2)
Note: f_{se} = 176.0 ksi	f_{si} = 205.0 ksi
(1) Assumed U'_t = 6.7 for clean strand condition	
(2) Assumed E_c = 4000 ksi	

5.2.5. Problems and Sources of Error

There is always human error involved when measurements are manually taken. In the transfer length tests, the greatest source of error is the measurements taken using the mechanical strain gauge. Transfer length tests took place under very uncomfortable conditions. First, the DEMEC points were located approximately 12 inches from the ground, making the readings very difficult to take. Second, because the beams were cast outside, all measurements were taken and recorded under intense heat in very hot summer weather.

DEMEC discs can also introduce error in the measurements when they are not completely bonded to the concrete surface. Although special care was taken when attaching the small steel discs, there could have been locations on the concrete surface where some discs moved during the readings.

The ambient temperature fluctuation could have also had an effect on the results. Some readings were taken at noon (under the sun), while others were taken at night (cool temperature).

The data clearly show the expected form for transfer length; linear strain over the end region of the beam, and a plateau following which indicates that transfer is complete. The problems listed above were overcome, and the transfer lengths given in Table 5.1 are supported by good data.

5.3. Development Length Tests

5.3.1. Determination of Development Length

As was explained in Section 3.7, the development length measurement requires an iterative process. An initial embedment length of 120 inches was chosen for the first test. This length was gradually reduced, as flexural failures were observed, to 93, 78 and 72 inches for the second, third and fourth tests respectively. Because no bond failure was observed with the 72 inch embedment length, a precise value for the development length could not be determined. It can only be stated that, for this project, the strand development is less than 72 inches. A shorter embedment length would have made a test meaningless for this 47.5 inch deep beam.

5.3.2. Moment Capacities

The ultimate moment capacity of the cross section, based on a strain compatibility analysis, is 3660 kip-ft. A plot of the moment versus curvature and the variation of the prestress force in top and bottom strands are included in Appendix C. The maximum total moment (including the applied load, the self weight of concrete beam and the weight of the spreader beam and bearing plates) is reported in Table 5.5 for each of the four tests. In Table 5.5, it can be seen that the values obtained from the tests correlate very well with the ultimate moment estimated using a strain compatibility analysis. A maximum error between the two values of less than 2% is reported, thus the analysis with actual material properties gives approximately the measured ultimate moment for each of these tests.

The moment - curvature plot in Figure C.1 utilizes the actual load versus strain curves (Figures B.1 - B.5) for the 0.6 inch diameter strand. The behavior of the concrete was modeled using the well known Hognestad's model. Only the actual compressive strength of the concrete slab was used in the model (See Figures B.6 and B.7), because at ultimate the compression is entirely in the slab. It is interesting to note that the bottom strands are more highly stressed at ultimate (approaching fracture) than the top strands. The stress in the bottom strands increases constantly with the applied moment, while the stress in the top strands decreases first and then increases at ultimate moment (See Figure C.2).

Table 5.5. Measured and Predicted Moment Capacities

Test	M_{test} (kip-ft)	M_u (kip-ft)	M_{test}/M_u
1-NSC-1-120	3680	3660	1.005
2-NSC-1-93	3690	3660	1.008
3-NSC-2-78	3690	3660	1.008
4-NSC-2-72	3600	3660	0.984

5.3.3. Comparison of Development Length with Previous Research

Results from previous studies on development length of 0.6-in. diameter strands in normal strength concrete are summarized in Table 5.6. Burdette et. al. [5] and Cousins et. al. [6] have reported development lengths from 85 to 132 inches for uncoated strands.

Russell and Burns [4] have reported transfer lengths, for AASHTO-type beams of 84 inches.

All previous studies report development lengths that are longer than the shortest embedment length tested in this project. The strand condition, which can affect significantly the development length of prestressing strands, was not clearly specified in all of the previous studies. In this research, the surface condition of the strands was clean.

There has been much discussion of possible differences in actual strand surface condition from different suppliers, but the strand in this study clearly had excellent bond properties. The short transfer length and short development length are quite consistent, both indicating excellent bond between strand and concrete.

Table 5.6. Development Lengths from Previous Research

Researchers	f'_c (psi)	Development Length (in)
Burdette et. al. (1994)	5130 - 7980	85
Cousins et. al. (1990)	6640	132 (1) 64 (2)
Russell & Burns (1993)	6360 - 7440 7020	84 (3) <78 (4)

(1) Uncoated strands

(2) Epoxy coated strands with grit

(3) AASHTO-type beams

(4) Rectangular beams

5.3.4. Comparison with Equations for Development Length

Several equations from Table 2.1 were used for estimating the development length of the 0.6-in diameter strands. The values found are reported in Table 5.7. The minimum calculated development length was 83.3 inches and the maximum was 160.8 inches. The ACI 318/AASHTO equation predicted a development length of 96.4 inches, which is greater than the minimum embedment length tested in this project. As noted above the strand clearly had excellent bond properties and the current ACI 318/ASSHTO is a safe equation to use in predicting development length for clean strand.

Table 5.7. Development Lengths From Selected Equations

Equation	Development Length (in)
ACI 318 / AASHTO [11,12]	96.4
Zia & Mostafa [17]	116.3
Cousins, Johnston & Zia [16]	160.8 (1)
Mitchell et. al. [9]	83.3
Burdette, Deatherage & Chew [5]	132.8
Buckner (FHWA) [19]	160.8 (2)

Note: f_{se} = 176.0 ksi f_{ps} = 278 ksi

f_{si} = 205.0 ksi f_{pu} = 280 ksi

(1) Assumed U'_d = 1.32 for clean strand condition

(2) Assumed $\lambda = 2.0$

5.3.5. Problems and Sources of Error

The major inconvenience encountered in the development tests series was that a bond failure did not occur. The development length of the 0.6-in. diameter prestressing strands at two-inch spacing in the fully bonded normal strength concrete composite Texas Type C beams could not be determined precisely. The shortest embedment length used in this study was 72 inches, which is the limit to avoid “deep beam” behavior in the girders tested in this study. The type of failure (compression strut) observed in the last test demonstrated that shorter embedment lengths cannot be tested.

There were no significant problems during the tests. All strain gauges, linear potentiometers and dial gauges worked well. At the beginning there were some problems with the hydraulic system (e.g. oil leakage from connections), but leaks were repaired before continuing with the test.

5.4. Effect of Variables

The variables affecting the transfer and development length of prestressing strands were mentioned in Section 2.4. Although the strands used in this study possessed a “bright” surface (no trace of rusting), they had excellent bond. During the fabrication of the beams, an important factor that contributed to the excellent bond was that none of the strands was contaminated with oil. Other studies have reported larger transfer and development lengths because they may have had different strand suppliers and/or surface conditions might have varied.

The fact that the strands were gradually released for the beams used in this study may have lead to slightly shorter transfer lengths than for studies with flame-cut strands. The development length might have also been slightly longer with flame cutting of the strands.

From the beginning of this study, it was decided to exclude the possibility of a shear failure in the beams, thus enough shear reinforcement was provided. The ACI 318 Code limits the contribution of the nominal shear strength provided by shear reinforcement (V_s) to a value smaller than $8\sqrt{f'_c}b_w d$. The limit in V_s is intended to prevent non ductile failures (strut compression failure) from occurring. The shear reinforcement placed in these beams had a V_s equal to $20\sqrt{f'_c}b_w d$. Based on the results obtained in the fourth test, it seems that the ACI formula contains a factor of safety of more than two.

CHAPTER SIX
SUMMARY AND CONCLUSIONS

6.1. Summary

This research focused on the transfer and development length of 0.6-inch diameter prestressing strand at two-inch spacing in normal strength concrete (NSC) beams. Straight fully bonded strands were used in the two beams. Four top strands were used, instead of draping or debonding some of the bottom strands, for controlling the high tensile concrete stresses that beams with only straight bottom strands develop at the ends during the transfer of the prestressing force. Two NSC beams were fabricated at Texas Concrete Company in Victoria, Texas. The beams were standard Texas Type C sections, which were 40 inches deep with a 7 inch thick web. Both beams were shipped to the Ferguson Structural Engineering Laboratory (FSEL) at The University of Texas at Austin where a reinforced concrete slab 7.5 inches thick by 72 inches wide was cast on top of each beam. The beams had design strengths of 4300 psi at release of the prestressing force and 7000 psi at 28 days. The concrete slab had a design strength of 6000 psi at 28 days.

Transfer length was determined by measuring the concrete strain at the center of gravity of the prestressing strand at the bottom of the beams. Measurements were taken at the prestressing plant using mechanical strain gauges (DEMEC gauges). Concrete strains were recorded and plotted with respect to length. From the resulting profile, the transfer length was determined.

Because the development length cannot be determined directly by a single test, an iterative approach was used. The method required that the embedment length, which is the length of bond from the beginning of bond to the critical section, be varied from test to test. An initial embedment length was chosen for the first test, then based on the results of the first test the embedment length for the second test was selected. The same procedure was used for subsequent tests. Failure mode was the parameter that determined the embedment length for the next test (e.g. if flexural failure had not occurred in the first test, then the embedment length would have been increased). Following this procedure the development length was estimated. Development length tests for these two beams resulted in flexural failure for all four tests having embedment lengths of 120, 93, 78 and 72 inches.

All tests were carried out at the FSEL at The University of Texas at Austin. Applied load, deflections, top fiber concrete strains and end slips were recorded for each of the four tests. Crack patterns were drawn for both faces of each beam, and the maximum crack width for each test was recorded.

6.2. Conclusions

The following conclusions can be reached based on data from this project, which involved 0.6-inch diameter strands with bright (no rust) surface conditions:

1) The average transfer length for 0.6-inch diameter strands is 21.6 inches based on the strain profiles. End slip measurements taken for the four ends of the two normal-strength concrete beams gave an estimate of 20.6 inches for transfer length for the same beams.

2) The development length for 0.6-inch diameter strands with clean surface condition in normal strength concrete is less than 72 inches. The four tests had ultimate moments within 2% of the ultimate moment predicted using a moment curvature analysis, actual material properties, and with a strain in the strands of approximately 3.5%.

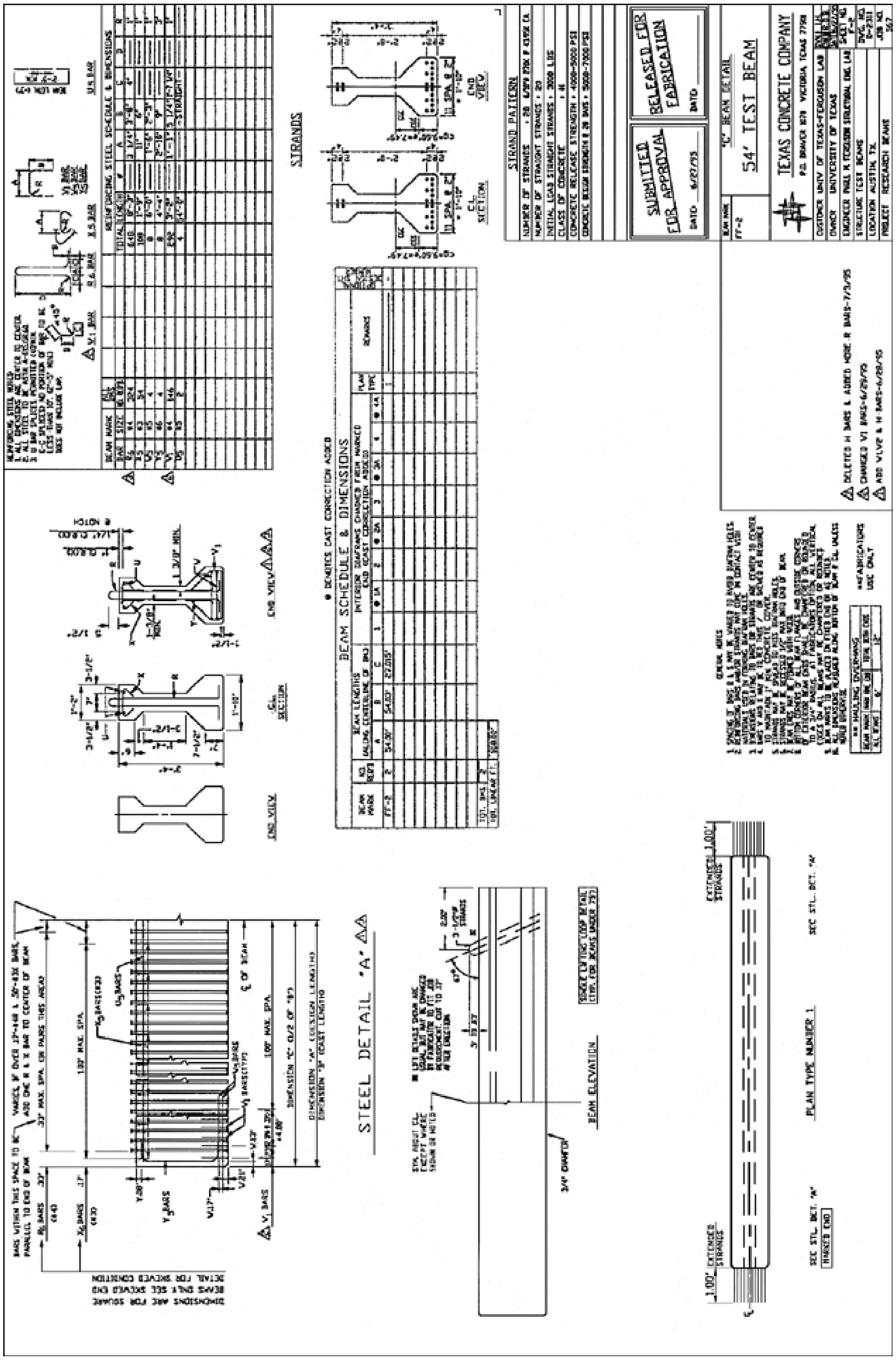
3) Significant end slip for the 0.6-inch strands at two inch spacing was not observed in any of the four development tests, even when the development length was only 72 inches.

4) The ACI 318/AASHTO equations for transfer and development length predicted values higher than those determined in this research program. The transfer length estimated by these codes is one and a half times the average transfer length obtained in this study. The upper bound of development length determined in this study showed the code equation to be conservative.

5) Crushing of the compression diagonal strut occurred at the end of the last test (NSC-2-N-72) following large deformations. The web concrete crushed throughout the shear span at failure. Analysis of the failure load showed that $V_s = 20\sqrt{f'_c} b_w d$ was actually reached at failure, exceeding the $8\sqrt{f'_c} b_w d$ limit of the ACI Code. For this test the ACI Code limit is shown to be quite conservative.

APPENDIX A

CONTRACTOR DRAWINGS FOR TEST SPECIMEN BEAMS



STEEL DETAIL 'A'
BEAM ELEVATION
PLAN TYPE NUMBER 1
END VIEW
SECTION
BEAM SCHEDULE & DIMENSIONS
STRANDS
STRAND PATTERN
SUBMITTED FOR APPROVAL
RELEASED FOR FABRICATION
54' TEST BEAM
TEXAS CONCRETE COMPANY

Figure A.1. Contractor Drawing for Test Specimen Beams

APPENDIX B

MATERIAL PROPERTY PLOTS

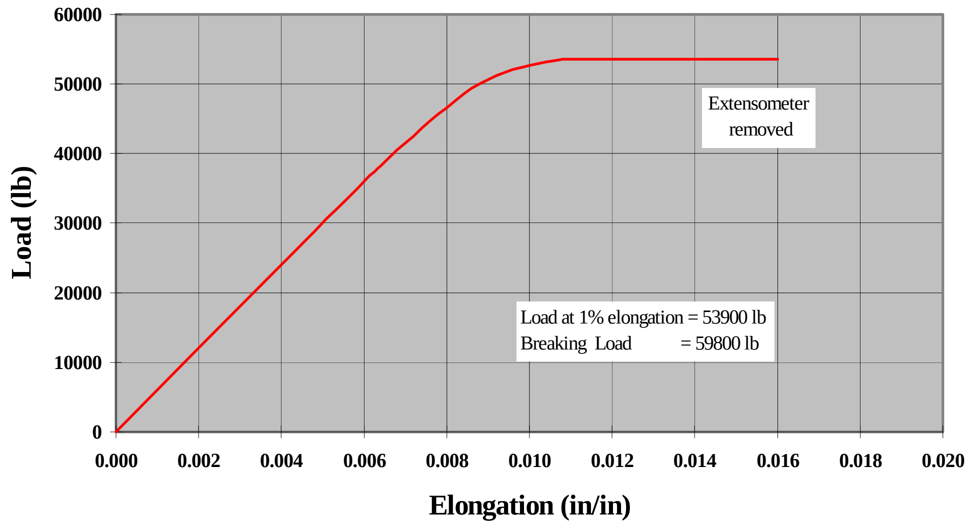


Figure B.1. Tensile Test Result (Strand Sample 1)

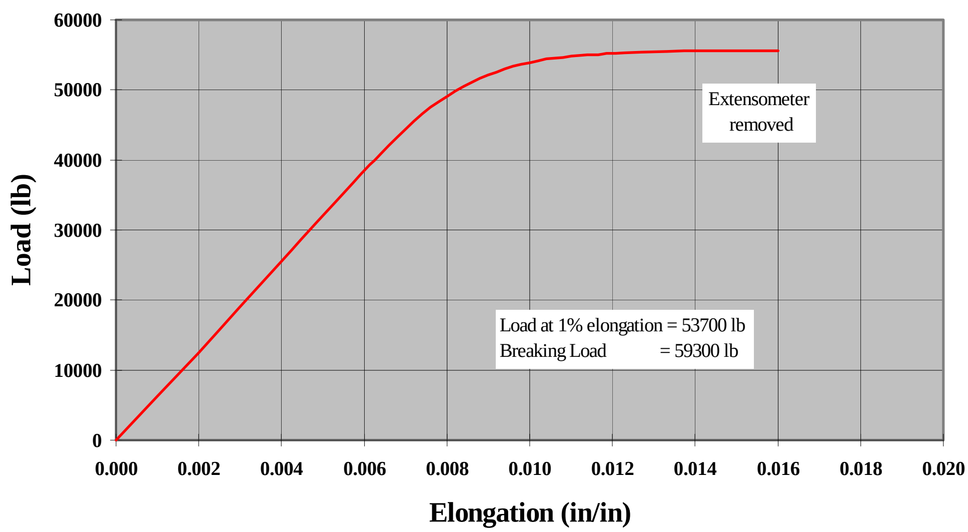


Figure B.2. Tensile Test Result (Strand Sample 2)

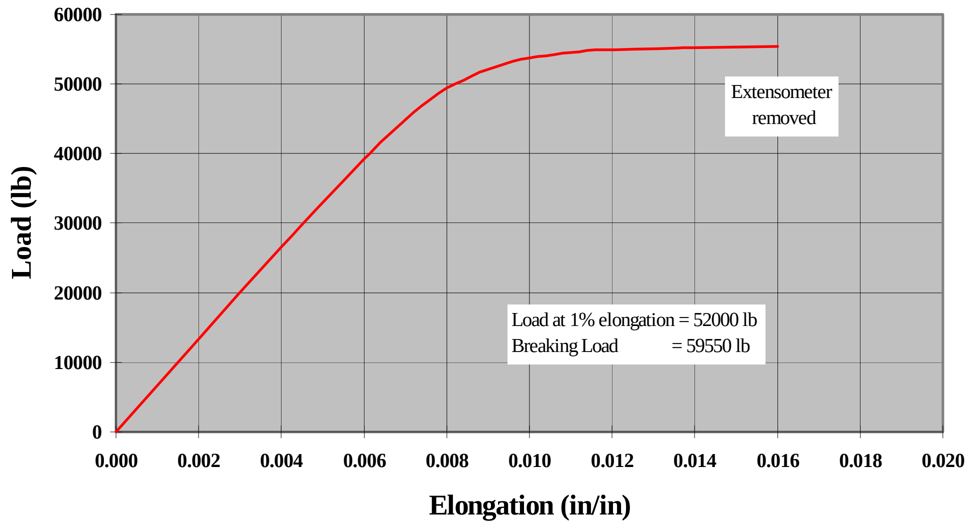


Figure B.3. Tensile Test Result (Strand Sample 3)

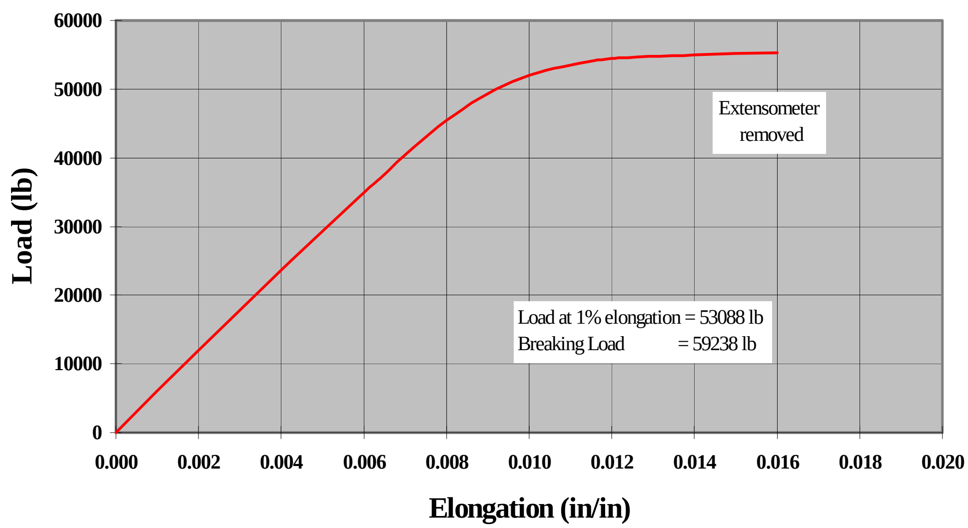


Figure B.4. Tensile Test Result (Strand Sample 4)

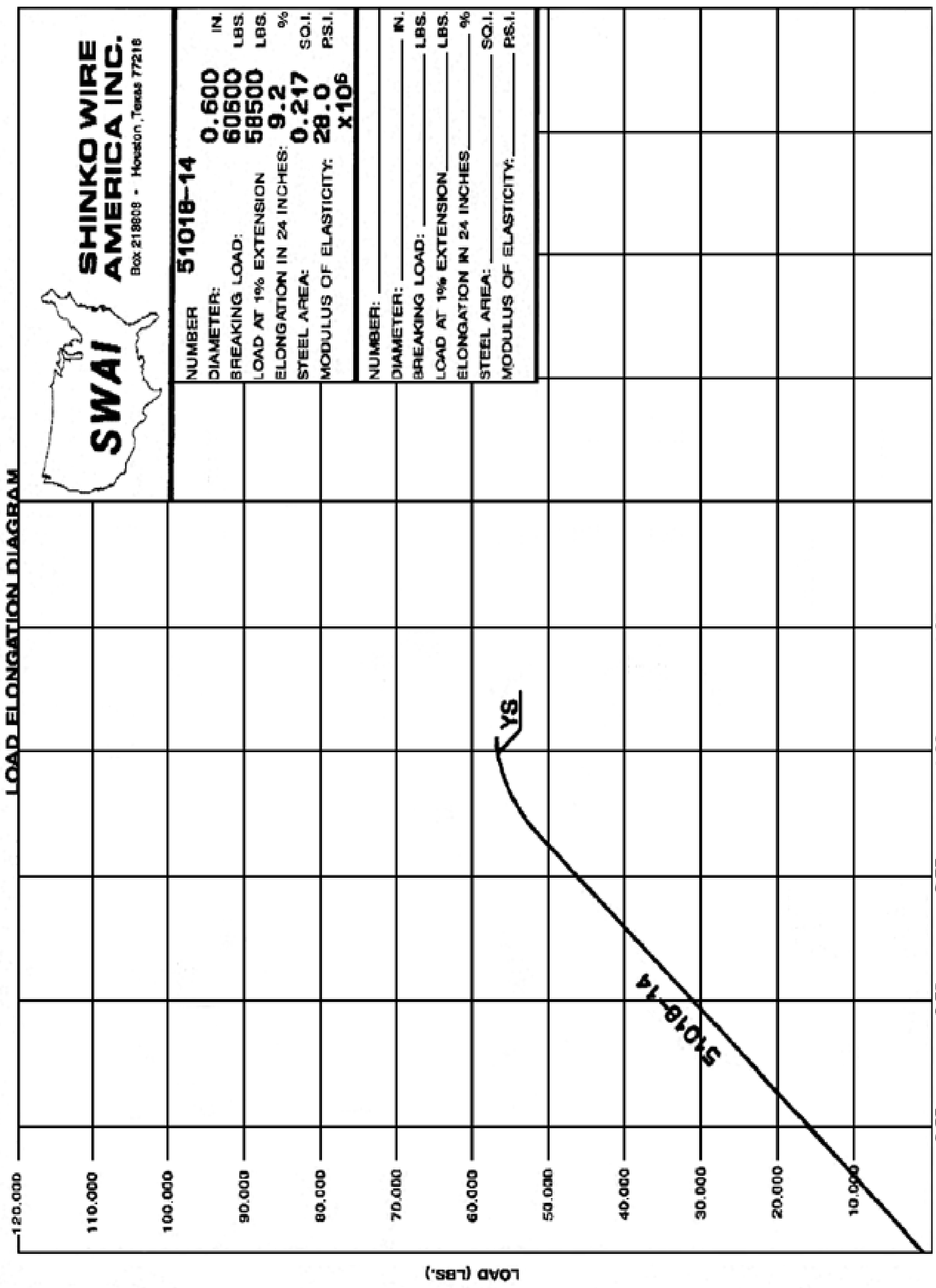


Figure B.5. Strand Manufacturer Tensile Test Result

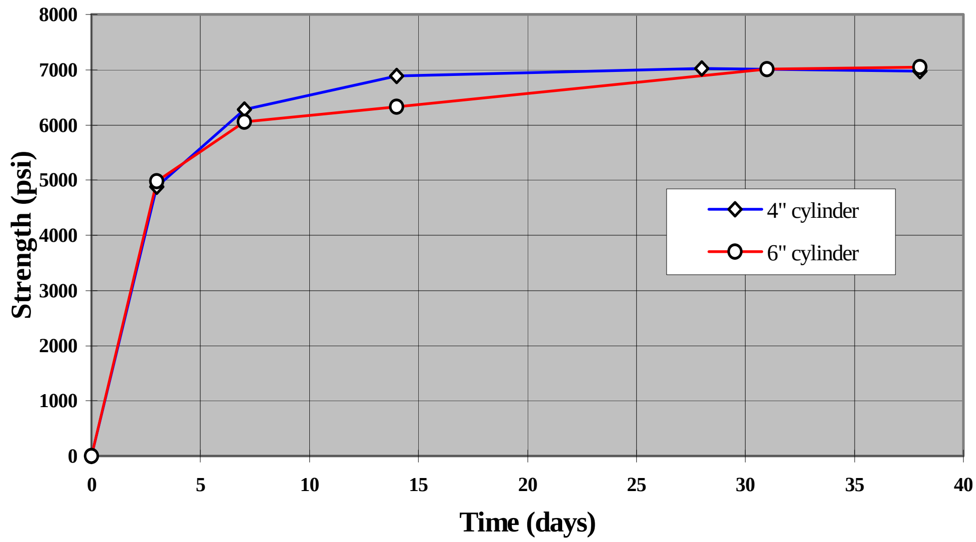


Figure B.6. Concrete Compressive Strength of First Slab

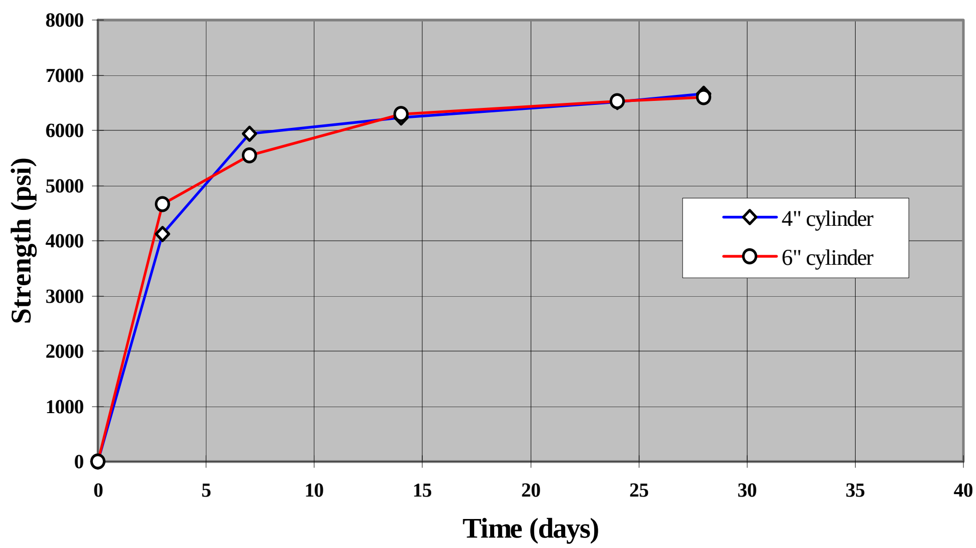


Figure B.7. Concrete Compressive Strength of Second Slab

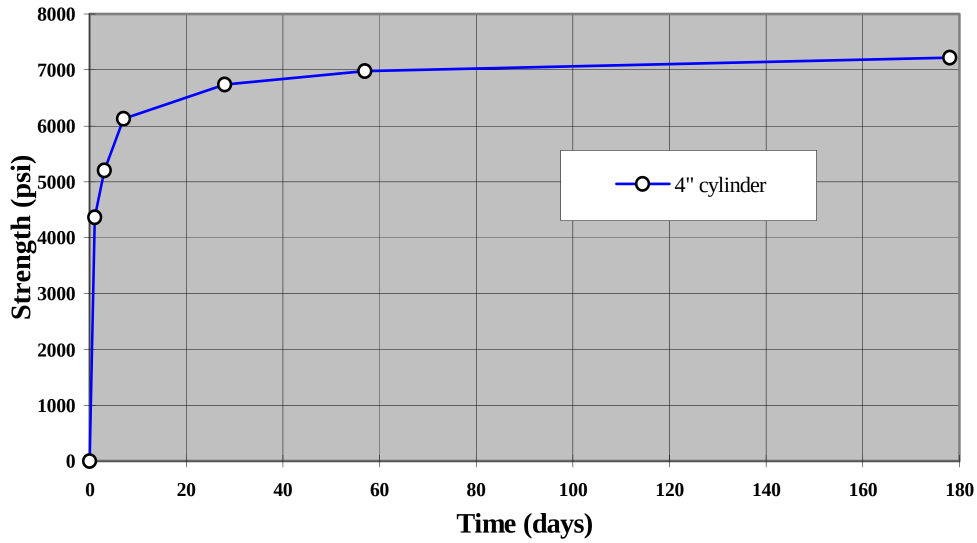


Figure B.8. Concrete Compressive Strength of Beam

APPENDIX C

MOMENT - CURVATURE ANALYSIS

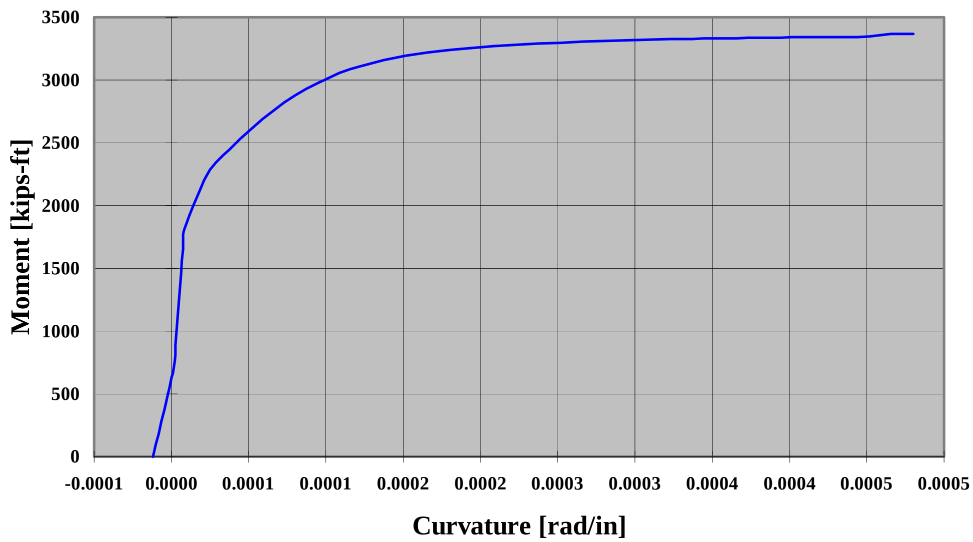


Figure C.1. Moment - Curvature for Specimen Cross Section

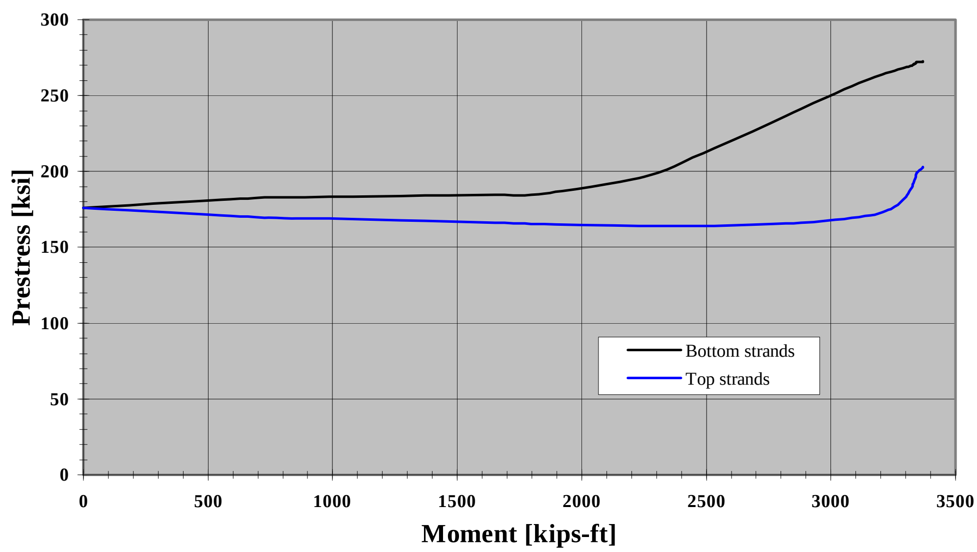


Figure C.2. Prestress vs. Moment

APPENDIX D

TRANSFER LENGTH MEASUREMENTS

Table D.1. Transfer Length Measurements (NSC-1-South)

End	Measured Strain				Average Strain		Smoothed Avg	
Dist.	East Face		West Face		South End		South End	
	7/11/95	1/2/96	7/11/95	1/2/96	7/11/95	1/2/96	7/11/95	1/2/96
(inches)	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$
4.92	0	0	212	504	106	504		
6.89	32	532	260	664	146	598	155	606
8.86	84	580	340	852	212	716	213	713
10.83	144	752	420	900	282	826	287	829
12.80	256	876	476	1016	366	946	365	937
14.76	352	1012	540	1064	446	1038	438	1035
16.73	400	1076	604	1164	502	1120	502	1107
18.70	480	1128	636	1200	558	1164	550	1154
20.67	508	1144	672	1212	590	1178	584	1188
22.64	524	1168	684	1276	604	1222	609	1234
24.61	576	1304	688	1300	632	1302	611	1263
26.57	520	1208	672	1324	596	1266	611	1285
28.54	540	1232	668	1344	604	1288	597	1281
30.51	524	1248	660	1332	592	1290	590	1273
32.48	512	1228	636	1256	574	1242	587	1257
34.45	548	1252	644	1224	596	1238	582	1239
36.42	512	1220	640	1252	576	1236	577	1221
38.39	508	1172	612	1208	560	1190	565	1211
40.35	504	1184	616	1228	560	1206	556	1190
42.32	496	1096	600	1252	548	1174	548	1185
44.29	484	1168	588	1184	536	1176	537	1169
46.26	472	1160	584	1156	528	1158	527	1153
48.23	452	1084	584	1168	518	1126	524	1147
50.20	472	1136	580	1180	526	1158	528	1135
52.17	480	1112	600	1128	540	1120		

Table D.2. Transfer Length Measurements (NSC-1-North)

End	Measured Strain				Average Strain		Smoothed Avg	
Dist.	East Face		West Face		North End		North End	
	7/11/95	1/8/96	7/11/95	1/8/96	7/11/95	1/8/96	7/11/95	1/3/96
(inches)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)
4.92	308	724	200	480	254	602		
6.89	312	676	252	640	282	658	293	679
8.86	392	848	296	704	344	776	341	767
10.83	432	904	364	828	398	866	402	856
12.80	520	1012	408	840	464	926	461	935
14.76	560	1032	484	996	522	1014	525	1026
16.73	628	1188	548	1088	588	1138	587	1130
18.70	712	1244	588	1232	650	1238	643	1211
20.67	728	1264	652	1252	690	1258	682	1267
22.64	736	1312	676	1300	706	1306	693	1299
24.61	712	1344	656	1320	684	1332	690	1299
26.57	720	1276	640	1244	680	1260	685	1292
28.54	736	1240	648	1328	692	1284	679	1264
30.51	688	1216	640	1280	664	1248	667	1254
32.48	672	1232	616	1228	644	1230	651	1237
34.45	676	1212	612	1256	644	1234	641	1223
36.42	696	1244	576	1168	636	1206	629	1202
38.39	660	1172	552	1160	606	1166	620	1179
40.35	644	1132	592	1196	618	1164	612	1168
42.32	640	1160	584	1188	612	1174	608	1158
44.29	616	1096	572	1176	594	1136	604	1152
46.26	644	1124	568	1168	606	1146	597	1150
48.23	648	1176	536	1160	592	1168	598	1156
50.20	640	1156	552	1152	596	1154	591	1159
52.17	628	1152	544	1156	586	1154		

Table D.3. Transfer Length Measurements (NSC-2-South)

End	Measured Strain				Average Strain		Smoothed Avg	
Dist.	East Face		West Face		South End		South End	
	7/11/95	1/19/96	7/11/95	1/19/96	7/11/95	1/19/96	7/11/95	1/19/96
(inches)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)	($1x10^{-6}$)
4.92	580	740	192	356	386	548		
6.89	568	684	256	488	412	586	426	627
8.86	624	812	336	680	480	746	475	730
10.83	656	976	412	740	534	858	527	803
12.80	688	836	448	772	568	804	584	916
14.76	800	1304	500	868	650	1086	645	989
16.73	856	1176	576	980	716	1078	708	1091
18.70	880	1220	636	1000	758	1110	754	1127
20.67	900	1248	676	1136	788	1192	788	1181
22.64	924	1292	712	1188	818	1240	766	1215
24.61	692	1216	692	1208	692	1212	755	1225
26.57	780	1204	732	1240	756	1222	736	1238
28.54	804	1276	716	1284	760	1280	738	1236
30.51	700	1172	696	1240	698	1206	722	1251
32.48	684	1196	732	1336	708	1266	723	1258
34.45	820	1312	708	1292	764	1302	718	1269
36.42	668	1224	696	1256	682	1240	725	1272
38.39	736	1220	720	1328	728	1274	780	1313
40.35	1176	1628	684	1224	930	1426	866	1390
42.32	1204	1680	676	1260	940	1470	907	1417
44.29	1056	1500	648	1208	852	1354	895	1406
46.26	1144	1612	644	1176	894	1394	881	1383
48.23	1148	1608	648	1192	898	1400	895	1393
50.20	1148	1604	640	1164	894	1384	886	1373
52.17	1088	1532	644	1140	866	1336		

Table D.4. Transfer Length Measurements (NSC-2-North)

End	Measured Strain				Average Strain		Smoothed Avg	
Dist.	East Face		West Face		North End		North End	
	7/11/95	1/19/96	7/11/95	1/19/96	7/11/95	1/19/96	7/11/95	1/19/96
(inches)	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$	$(1x10^{-6})$
4.92	144	372	240	636	192	504		
6.89	192	364	288	616	240	490	253	549
8.86	312	644	344	664	328	654	319	636
10.83	380	728	400	800	390	764	395	735
12.80	480	676	452	896	466	786	475	833
14.76	612	896	528	1000	570	948	571	941
16.73	724	960	632	1216	678	1088	667	1079
18.70	808	1208	696	1196	752	1202	751	1204
20.67	876	1344	768	1300	822	1322	795	1285
22.64	868	1356	752	1304	810	1330	818	1324
24.61	880	1352	764	1288	822	1320	821	1349
26.57	896	1412	768	1380	832	1396	833	1381
28.54	920	1428	772	1428	846	1428	832	1413
30.51	868	1384	768	1444	818	1414	821	1414
32.48	840	1364	756	1436	798	1400	798	1368
34.45	824	1248	732	1332	778	1290	775	1327
36.42	788	1248	712	1332	750	1290	755	1282
38.39	744	1156	728	1376	736	1266	729	1275
40.35	680	1172	724	1364	702	1268	704	1259
42.32	632	1112	716	1372	674	1242	680	1245
44.29	632	1116	696	1332	664	1224	661	1226
46.26	628	1140	660	1284	644	1212	655	1210
48.23	636	1100	676	1288	656	1194	658	1197
50.20	652	1024	696	1344	674	1184	662	1181
52.17	636	1056	676	1272	656	1164		

Table D.5. End Slip Measurements at Transfer

Strand Label	NSC-1-Beam		NSC-2-Beam	
	South End (in)	North End (in)	South End (in)	North End (in)
A1	0.0843	0.0643	0.0813	0.0775
A2	0.0775	0.0402	0.0899	0.0794
A3	0.0844	0.0653	0.0923	0.0653
A4	0.0754	0.0579	0.0775	0.0688
A5	0.0581	0.0775	0.0940	0.0659
A6	0.0525	0.0661	0.0710	0.0671
A7	0.0720	0.0608	0.0821	0.0984
A8	0.0811	0.0655	0.0773	0.0624
A9	0.0616	0.0657	0.0704	0.0726
A10	0.0612	0.0502	0.0739	0.0735
B1	0.0812	0.0652	0.0761	0.0874
B2	0.0635	0.0576	0.0734	0.0713
B3	0.0508	0.0670	0.0852	0.0759
B4	0.0508	0.0593	0.0728	0.0665
B5	0.0662	0.0648	0.0733	0.0695
B6	0.0622	0.0607	0.0763	0.0772
C1	0.0781	0.0981	0.0878	0.1148
C2	0.0904	0.0951	0.0734	0.0981
D1	0.0869	0.0999	0.0846	0.1145
D2	0.0773	0.0890	0.0648	0.0890
Avg.	0.0708	0.0685	0.0789	0.0798

APPENDIX E

DEVELOPMENT LENGTH MEASUREMENTS

Table E.1. Deflection Measurements (NSC-1-South-120)

Applied Load (kips)	Max Deflection (in)	Avg North Deflection (in)	Avg South Deflection (in)	Max Net Deflection (in)
0	0.000	0.000	0.000	0.000
31	0.055	0.002	0.064	0.027
79	0.089	0.005	0.088	0.049
119	0.116	0.008	0.102	0.068
160	0.141	0.011	0.111	0.087
200	0.164	0.015	0.120	0.104
241	0.187	0.018	0.129	0.121
280	0.209	0.022	0.137	0.138
318	0.232	0.025	0.143	0.157
318	0.233	0.025	0.143	0.157
317	0.233	0.025	0.144	0.157
361	0.257	0.028	0.151	0.177
401	0.281	0.032	0.157	0.196
441	0.307	0.035	0.163	0.217
460	0.329	0.036	0.165	0.237
478	0.374	0.037	0.170	0.280
500	0.421	0.038	0.173	0.326
520	0.478	0.040	0.176	0.380
540	0.553	0.041	0.179	0.453
559	0.633	0.043	0.182	0.531
580	0.740	0.044	0.186	0.635
600	0.849	0.044	0.189	0.743
620	0.989	0.045	0.192	0.881
640	1.192	0.046	0.197	1.082
645	1.300	0.046	0.199	1.189
649	1.407	0.046	0.200	1.295
651	1.511	0.046	0.201	1.399
655	1.620	0.046	0.203	1.507
657	1.725	0.046	0.204	1.611

Table E.1. Deflection Measurements (NSC-1-South-120)

Applied Load (kips)	Max Deflection (in)	Avg North Deflection (in)	Avg South Deflection (in)	Max Net Deflection (in)
660	1.831	0.047	0.205	1.716
663	1.935	0.047	0.206	1.820
665	2.039	0.047	0.208	1.923
667	2.143	0.048	0.209	2.026
669	2.247	0.048	0.210	2.130
672	2.351	0.048	0.211	2.233
673	2.454	0.048	0.212	2.336
674	2.555	0.048	0.213	2.437
400	1.814	0.039	0.182	1.714
201	1.290	0.023	0.151	1.213
8	0.718	0.001	0.061	0.691

Table E.2. Concrete Strain Measurements (NSC-1-South-120)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
0	1	0	0	-1	0	-1	0	0
31	-21	-22	-23	-30	-24	-25	-25	-24
79	-53	-55	-55	-74	-58	-60	-61	-60
119	-82	-84	-81	-107	-86	-91	-91	-89
160	-110	-115	-110	-143	-115	-122	-124	-120
200	-139	-145	-138	-179	-145	-153	-156	-151
241	-166	-175	-166	-216	-175	-183	-188	-182
280	-197	-204	-194	-251	-204	-213	-220	-213
318	-226	-235	-223	-289	-234	-244	-252	-244
318	-225	-235	-224	-289	-235	-242	-253	-244
317	-225	-235	-224	-289	-234	-244	-252	-244
361	-258	-269	-255	-327	-265	-275	-286	-279
401	-288	-301	-285	-366	-297	-308	-320	-311
441	-324	-337	-317	-407	-331	-342	-355	-347
460	-356	-372	-348	-453	-370	-372	-385	-376
478	-414	-431	-405	-541	-444	-434	-453	-442
500	-478	-496	-463	-619	-514	-493	-518	-512
520	-560	-579	-528	-699	-586	-556	-592	-587
540	-658	-676	-599	-790	-663	-631	-683	-682
559	-753	-772	-670	-874	-737	-703	-769	-773
580	-862	-884	-757	-976	-827	-791	-878	-885
600	-984	-1003	-845	-1085	-927	-875	-982	-1000
620	-1137	-1149	-961	-1239	-1062	-994	-1113	-1140
640	-1356	-1363	-1137	-1466	-1260	-1167	-1296	-1338
645	-1484	-1491	-1244	-1620	-1386	-1271	-1401	-1451
649	-1600	-1605	-1344	-1761	-1506	-1368	-1497	-1556
651	-1714	-1716	-1445	-1892	-1624	-1465	-1603	-1674
655	-1821	-1816	-1533	-2005	-1726	-1550	-1702	-1781
657	-1940	-1929	-1628	-2125	-1831	-1646	-1803	-1896

Table E.2. Concrete Strain Measurements (NSC-1-South-120)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
660	-2051	-2038	-1722	-2236	-1923	-1731	-1903	-2004
663	-2165	-2151	-1813	-2343	-2010	-1816	-2000	-2111
665	-2279	-2261	-1904	-2447	-2093	-1896	-2094	-2219
667	-2402	-2385	-1999	-2550	-2178	-1982	-2190	-2327
669	-2516	-2502	-2090	-2642	-2258	-2064	-2285	-2431
672	-2621	-2604	-2172	-2728	-2332	-2139	-2369	-2523
673	-2738	-2732	-2265	-2821	-2411	-2223	-2465	-2629
674	-2856	-2867	-2360	-2915	-2490	-2307	-2565	-2735
400	-2226	-2267	-1823	-2356	-1968	-1794	-1978	-2107
201	-1679	-1710	-1368	-1850	-1515	-1361	-1474	-1574
8	-1014	-976	-787	-1152	-955	-767	-856	-900
6	-1000	-962	-772	-1138	-942	-754	-843	-887
4	-986	-950	-760	-1127	-932	-746	-833	-878
0	-972	-934	-745	-1107	-916	-730	-818	-863

Table E.3A. End Slip Measurements (NSC-1-South-120)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	-11	0	52	-20	14	39	4	-27	14	-4
31	-58	6	-1246	-22	-30	-137	22	-7	-18	-18
79	-107	0	-2331	-30	-50	-178	3	-5	-13	-14
119	-123	-8	-2587	-6	-2	-198	3	-9	-31	-86
160	-127	-20	-2793	-1	902	-200	-26	-8	-83	-98
200	-94	-46	-2862	-2	171	-171	-20	-11	-116	-64
241	-363	-108	-3842	-16	659	-207	-28	-3	-162	-94
280	-544	-261	-4487	-32	533	-193	-26	-17	-180	-72
318	-467	-214	467	-34	-145	-186	-20	-21	-127	-62
318	-752	-130	-624	-18	506	-207	-5	-17	-27	-78
317	-751	-144	-2209	-36	607	-191	-24	-25	-73	-82
361	-728	-197	-254	-11	-373	-200	-8	-17	-116	-45
401	-1156	-184	4760	-40	145	-182	37	-24	-157	-44
441	-949	-111	2307	-28	1381	-173	9	-34	-16	14
460	-1172	-255	-3969	-14	669	-126	-8	-40	-39	47
478	-947	-297	-5845	10	39	-44	-29	-31	73	343
500	-1055	-380	-8994	-29	-36	-83	-57	-44	10	379
520	-1080	-479	-8879	-12	156	-70	-48	-27	79	356
540	-923	-424	-9230	-25	399	2	-5	-31	-54	369
559	-701	-473	-5610	-20	-197	21	-17	-23	-44	370
580	-687	-417	-6436	-21	-82	20	50	-27	4	331
600	-585	-493	-7340	-31	-356	33	-36	-61	-134	283
620	-446	-426	-7337	-18	-1552	64	-29	-7	-97	344
640	-391	-418	-7881	-42	-2336	98	-25	-47	118	-221
645	-363	-503	-8041	-16	-2509	92	-7	-57	30	-426
649	-300	-489	-6046	-19	-1991	92	-6	-21	37	-491
651	-311	-468	-7275	-21	-2629	144	-8	-41	36	-621
655	-611	-479	-7433	-23	-2548	118	-49	-105	8	-907
657	-469	-565	-6896	-30	-2017	87	-63	-108	-18	-1103

NOTE: All measurements were multiplied by 10^6

Table E.3A. End Slip Measurements (NSC-1-South-120)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
660	-477	-622	-8523	-23	-2166	89	-59	-92	41	-1351
663	-741	-411	-8131	-37	-2532	67	-54	-98	-66	-1327
665	-966	-554	-6455	-15	-2237	-55	-70	-108	-141	-1255
667	-1088	-375	-5108	-28	-2642	-180	-90	-121	-71	-1127
669	-1640	-356	-5924	-30	-2433	-213	-107	-54	-70	-1525
672	-1555	-348	-7570	-40	-2419	-281	-141	-39	-56	-1720
673	-1441	-423	-8211	-33	-2232	-361	-96	-319	23	-1939
674	-1392	-596	-7563	-20	-2622	-165	-128	-331	64	-1994
400	-1282	-450	-9356	-79	-1961	44	-95	-148	16	-1681
201	-1225	-457	-8998	-92	537	1581	148	-91	44	-1580
8	-40	628	3833	388	1318	1968	1076	374	2712	-1889
6	-117	623	4617	343	970	2069	1064	449	2184	-1924
4	-200	607	6006	268	1049	885	1027	419	3270	-1945
0	11	547	4582	199	1653	1167	1045	475	3398	-1857

NOTE: All measurements were multiplied by 10^6

Table E.3B. End Slip Measurements (NSC-1-South-120)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	East	West	East	West
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	0	-4	-5	1	-30	13	-6	-12	-3	2
31	-6	10	5	-83	-220	-17	-8	0	-3	4
79	15	40	7	-104	-226	87	2	-12	7	18
119	3107	52	-7	-150	-255	115	-22	-16	17	16
160	3060	43	-6	-80	-261	128	-17	-27	-12	5
200	2826	68	1	-55	-257	199	0	-12	3	6
241	2864	83	-17	-79	-253	251	18	-18	-19	12
280	3073	143	-21	-83	-267	243	-4	-24	13	14
318	3361	240	-12	-2	-247	273	10	-4	12	8
318	3470	304	-29	10	-265	279	18	-28	1	14
317	3526	356	-25	59	-241	264	8	-10	-5	2
361	3487	246	-7	272	-272	243	33	-19	-10	1
401	3181	322	-6	401	-273	228	-18	-12	14	16
441	3059	474	1	815	-251	257	21	-10	-6	0
460	4167	332	-12	762	-261	308	32	-10	8	10
478	4694	284	21	-321	-271	260	44	4	9	33
500	4638	263	3	-332	-301	220	23	-30	17	-2
520	4828	282	-2	-317	-284	209	36	-13	27	19
540	5330	1103	-8	357	-275	217	7	-24	20	0
559	5039	467	9	148	-268	240	4	-4	23	1
580	5168	1816	7	85	-285	258	7	-28	33	-16
600	5459	1403	82	1022	-310	262	4	-27	14	-21
620	5706	1544	232	1616	-294	275	24	-29	24	-1
640	5550	1215	331	2032	-274	261	-7	-52	19	-14
645	5451	1221	305	1170	-294	255	7	-65	1	-24
649	5946	1195	332	628	-275	267	-1	-62	6	-12
651	6094	1228	313	615	-280	288	-20	-99	3	-7
655	4968	1208	227	888	-284	261	-13	-117	-5	10
657	5891	1229	230	785	-268	210	-4	-128	-8	-13

NOTE: All measurements were multiplied by 10^6

Table E.3B. End Slip Measurements (NSC-1-South-120)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	East	West	East	West
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
660	6008	1228	300	939	-284	180	-5	-115	6	-6
663	5101	1242	305	713	-244	139	-13	-147	-8	-9
665	6109	1234	284	843	-257	6	-17	-157	-28	-2
667	5043	1198	258	1195	-268	-59	-14	-165	-13	-11
669	5986	1210	265	928	-248	-148	-6	-172	-29	-27
672	6173	1180	261	1036	-232	-218	-36	-172	-35	-13
673	6260	1187	252	1251	-244	-296	-11	-182	-56	-18
674	5916	1192	268	1329	-225	-364	-33	-203	-40	-18
400	5366	361	352	1903	-210	-488	-19	-195	-50	-13
201	5308	334	843	3025	2169	-459	-28	-208	-49	-30
8	3789	2125	1136	3331	5354	575	-6	-193	-40	-14
6	3720	2128	1133	3392	5402	543	-13	-199	-48	7
4	3734	2141	1129	3384	5375	537	-26	-194	-43	-14
0	3605	2124	1131	3292	5412	550	-9	-196	-51	-7

NOTE: All measurements were multiplied by 10^6

Table E.4. Deflection Measurements (NSC-1-North-93)

Applied Load	Max Deflection	Avg North Deflection	Avg South Deflection	Max Net Deflection
(kips)	(in)	(in)	(in)	(in)
0	0.000	0.000	0.000	0.000
0	0.000	0.000	0.000	0.000
44	0.037	0.033	0.001	0.018
195	0.112	0.072	0.007	0.067
381	0.263	0.120	0.026	0.182
521	0.438	0.153	0.042	0.332
540	0.482	0.155	0.043	0.374
559	0.534	0.157	0.044	0.425
581	0.605	0.159	0.045	0.493
602	0.677	0.161	0.045	0.564
623	0.760	0.163	0.046	0.646
630	0.795	0.164	0.046	0.680
646	0.867	0.166	0.047	0.751
651	0.888	0.166	0.047	0.772
674	1.010	0.169	0.049	0.891
690	1.119	0.170	0.049	0.999
700	1.228	0.173	0.049	1.106
709	1.344	0.175	0.050	1.221
715	1.451	0.176	0.050	1.327
721	1.548	0.177	0.051	1.424
727	1.653	0.177	0.051	1.528
731	1.756	0.178	0.051	1.631
735	1.862	0.178	0.052	1.737
737	1.954	0.179	0.052	1.828
742	2.050	0.179	0.051	1.924
740	2.133	0.180	0.051	2.007
739	2.139	0.180	0.051	2.012
743	2.242	0.180	0.051	2.116
740	2.243	0.180	0.051	2.117
748	2.344	0.182	0.051	2.216
752	2.444	0.182	0.050	2.316
757	2.545	0.183	0.050	2.418
515	2.019	0.167	0.043	1.904
309	1.438	0.133	0.030	1.348
53	0.858	0.075	0.012	0.809
5	0.773	0.050	0.009	0.741

Table E.5. Concrete Strain Measurements (NSC-1-North-93)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
0	0	0	0	0	0	0	0	0
0	0	1	2	0	1	1	1	-1
44	-15	-16	-5	-15	-15	-8	-10	-16
195	-74	-85	-38	-68	-72	-49	-61	-74
381	-219	-257	-167	-207	-213	-187	-230	-224
521	-432	-505	-370	-453	-455	-357	-480	-448
540	-487	-566	-414	-501	-503	-403	-540	-504
559	-548	-631	-462	-555	-557	-459	-609	-566
581	-626	-719	-519	-627	-621	-525	-701	-643
602	-717	-812	-571	-701	-687	-580	-787	-716
623	-800	-905	-634	-781	-756	-653	-885	-795
630	-842	-950	-659	-818	-789	-679	-923	-825
646	-902	-1017	-705	-875	-847	-729	-992	-884
651	-920	-1037	-720	-894	-865	-745	-1012	-903
674	-1036	-1163	-810	-1003	-974	-830	-1130	-1005
690	-1132	-1269	-892	-1106	-1074	-924	-1236	-1090
700	-1229	-1376	-977	-1227	-1186	-1015	-1347	-1181
709	-1323	-1480	-1063	-1343	-1293	-1118	-1449	-1272
715	-1421	-1582	-1144	-1453	-1391	-1207	-1552	-1358
721	-1516	-1683	-1223	-1560	-1483	-1300	-1657	-1448
727	-1608	-1783	-1300	-1656	-1572	-1385	-1758	-1535
731	-1705	-1884	-1375	-1747	-1658	-1472	-1859	-1620
735	-1808	-1995	-1456	-1848	-1754	-1539	-1974	-1713
737	-1902	-2061	-1528	-1940	-1838	-1642	-2083	-1792
742	-1997	-2147	-1599	-2029	-1920	-1727	-2184	-1867
740	-2111	-2231	-1666	-2109	-1991	-1769	-2275	-1926
739	-2113	-2231	-1667	-2110	-1992	-1771	-2276	-1928
743	-2229	-2338	-1741	-2200	-2072	-1867	-2369	-1989
740	-2229	-2338	-1741	-2199	-2071	-1867	-2370	-1988
748	-2332	-2434	-1812	-2287	-2149	-1947	-2461	-2049
752	-2420	-2520	-1882	-2371	-2223	-2061	-2549	-2108
757	-2507	-2569	-1945	-2445	-2286	-2133	-2627	-2163
515	-2091	-2043	-1594	-2090	-1946	-1723	-2231	-1732
309	-1502	-1449	-1132	-1566	-1468	-1235	-1639	-1222
53	-859	-941	-670	-1017	-971	-734	-1044	-744
5	-761	-885	-600	-935	-898	-658	-967	-680

Table E.6A. End Slip Measurements (NSC-1-North-93)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	0	0	0	0	0	0	0	0	0	0
0	-46	3	-1	-5	-164	292	78	-337	-13	-215
44	-76	-14	-174	-5	-216	-11	39	-284	100	-295
195	-95	-57	529	-12	1223	875	20	-228	92	-251
381	137	-630	-1549	2	519	1116	33	-46	-30	-404
521	-2202	1216	-2008	207	-808	1493	486	-495	12	-1222
540	-1984	1145	-3325	178	-558	3211	504	-489	-60	-1159
559	-1922	1060	-638	174	-614	3871	583	-490	-108	-838
581	-1989	1051	-2346	243	-287	3310	666	-496	-81	-784
602	-2168	1082	-206	258	302	3574	694	-540	-99	-721
623	-995	1053	-1786	311	277	4839	650	-554	99	-846
630	-1328	1805	2457	218	359	5162	716	-504	492	156
646	-1242	1819	1773	152	358	5344	791	-515	501	29
651	-1195	1773	1808	111	274	5639	930	-493	493	12
674	-1159	1284	273	98	213	4690	934	-572	360	-869
690	-1052	1156	355	373	-7	8499	1010	-565	317	-1139
700	-919	1381	1574	593	985	11774	765	-387	231	-137
709	-790	1390	643	642	1214	12209	817	-376	211	-121
715	-750	1349	-4295	634	1054	11656	807	-401	61	-90
721	-657	1326	-5992	379	1649	11627	961	-601	12	-530
727	-717	1265	-4415	521	1434	11092	928	-596	30	-579
731	-768	1277	-5786	526	1170	11449	890	-570	35	-624
735	-760	1267	-2498	158	1312	11733	920	-596	67	-633
737	-882	1246	-6310	480	1097	11632	891	-581	102	-678
742	-709	1262	-8770	291	1011	12288	1028	-581	40	-659
740	-1492	1345	-1639	356	-935	12903	1104	-629	-230	-971
739	-1446	1349	-586	373	-953	12864	1092	-600	-230	-903
743	-874	1191	1986	479	-541	12966	1100	-606	-216	-1166
740	-869	1213	1304	483	-584	12960	1086	-586	-228	-1154
748	-747	1222	4009	502	-177	13052	1085	-611	-217	-1407
752	-622	1225	3248	501	1875	13299	1076	-608	-244	-1523
757	-579	1217	1813	499	867	13138	1059	-614	-246	-1512
515	-229	1192	2684	396	1554	12185	950	-575	-225	-1773
309	-219	1159	2208	355	712	14164	1134	-530	-225	-1896
53	-867	1944	-2858	2798	5242	13985	4346	2620	2569	653
5	-285	2202	1721	3087	5028	13411	4305	2678	3085	1766

NOTE: All measurements were multiplied by 10^6

Table E.6B. End Slip Measurements (NSC-1-North-93)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	East	West	West	East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	0	0	0	0	0	0	0	0	0	0
0	-24	34	-3	50	-2	-34	-74	-931	17	20
44	-29	1	-4	94	4	-39	-7	-818	101	35
195	2	-1	-1	112	8	16	18	-729	155	53
381	75	-34	-29	94	-18	241	96	-842	238	93
521	-430	106	-598	1091	-973	-390	205	1715	907	82
540	-417	80	-595	1152	-995	-447	174	1733	937	81
559	-506	32	344	422	-982	-185	178	1750	956	85
581	-174	-33	4136	540	-966	-318	179	1764	962	79
602	-551	-17	6058	680	-715	209	199	1759	984	86
623	-207	-36	8198	1495	-823	-63	199	1755	972	80
630	620	68	11826	1345	-247	187	169	1896	1007	95
646	659	48	12503	2637	-202	112	176	1893	980	78
651	675	49	12901	2854	-176	104	202	1908	1015	98
674	882	90	15248	3576	1006	2342	177	1886	959	81
690	958	354	17764	5355	1872	2405	166	1761	944	94
700	3630	310	19005	16217	2018	5966	99	1722	907	101
709	3648	332	19058	15580	2034	6007	114	1581	895	101
715	3675	343	19156	15751	2040	5993	92	1596	918	97
721	3655	278	19269	17068	2086	6073	-51	1935	943	163
727	3652	246	20570	17157	2095	6014	0	1924	931	144
731	3685	1600	20581	15113	2141	5987	-39	2036	971	161
735	3717	1550	20651	15569	2149	5986	-33	2144	996	166
737	3714	1537	20762	15917	2164	5889	-26	2039	1001	175
742	3202	1937	20827	15878	2097	6074	-40	1536	985	158
740	3271	1774	20888	17302	3987	5879	51	1772	1400	464
739	3276	1790	20900	17290	3993	5875	61	1779	1396	460
743	3308	1774	21174	18861	4029	5875	57	1785	1420	440
740	3308	1789	21200	18883	4019	5868	71	1787	1413	461
748	3325	1757	21220	18930	4032	5866	54	1757	1411	435
752	3324	1770	21261	19224	4053	5869	61	1769	1396	454
757	3347	1749	21287	19140	4049	5883	44	1764	1385	456
515	3364	2167	22118	19403	4277	5689	83	1737	1371	446
309	3403	2349	22158	18829	4763	5777	37	1721	1381	452
53	3886	5266	22595	19679	6750	6938	39	1728	1366	444
5	4934	6419	22686	19839	7101	6968	47	1725	1368	444

NOTE: All measurements were multiplied by 10^6

Table E.7. Deflection Measurements (NSC-2-South-78)

Applied Load (kips)	Max Deflection (in)	Avg North Deflection (in)	Avg South Deflection (in)	Max Net Deflection (in)
0	0.002	0.000	0.000	0.002
40	0.043	0.000	0.049	0.025
83	0.067	0.001	0.063	0.043
120	0.086	0.003	0.073	0.057
160	0.105	0.005	0.083	0.072
199	0.125	0.006	0.092	0.087
239	0.143	0.008	0.099	0.101
279	0.163	0.011	0.107	0.117
320	0.185	0.013	0.115	0.135
359	0.204	0.015	0.122	0.149
398	0.223	0.017	0.128	0.165
420	0.237	0.019	0.133	0.176
438	0.245	0.020	0.136	0.183
458	0.258	0.022	0.139	0.193
478	0.269	0.023	0.143	0.201
498	0.280	0.024	0.145	0.211
518	0.291	0.025	0.149	0.220
539	0.307	0.026	0.152	0.234
558	0.323	0.028	0.155	0.248
579	0.350	0.028	0.158	0.273
599	0.383	0.029	0.161	0.305
618	0.421	0.030	0.164	0.342
638	0.477	0.031	0.167	0.396
657	0.522	0.031	0.169	0.440
666	0.542	0.032	0.171	0.459
676	0.579	0.033	0.172	0.494
686	0.607	0.033	0.173	0.522
698	0.653	0.034	0.175	0.567
717	0.738	0.035	0.178	0.650

Table E.7. Deflection Measurements (NSC-2-South-78)

Applied Load	Max Deflection	Avg North Deflection	Avg South Deflection	Max Net Deflection
(kips)	(in)	(in)	(in)	(in)
725	0.772	0.035	0.179	0.684
738	0.826	0.035	0.180	0.737
758	0.950	0.036	0.183	0.860
776	1.042	0.035	0.185	0.951
780	1.087	0.036	0.185	0.996
793	1.215	0.036	0.187	1.123
799	1.280	0.036	0.189	1.188
801	1.324	0.036	0.189	1.232
807	1.422	0.035	0.190	1.329
812	1.522	0.035	0.190	1.429
813	1.578	0.035	0.190	1.485
817	1.617	0.035	0.191	1.524
818	1.685	0.035	0.191	1.592
819	1.709	0.035	0.191	1.616
820	1.810	0.035	0.192	1.717
827	2.014	0.035	0.193	1.920
829	2.117	0.035	0.194	2.023
833	2.179	0.035	0.194	2.085
832	2.218	0.035	0.195	2.124
838	2.316	0.035	0.195	2.222
842	2.406	0.035	0.196	2.312
841	2.521	0.035	0.196	2.427
807	2.526	0.034	0.195	2.433
599	2.041	0.028	0.175	1.959
397	1.611	0.019	0.148	1.544
201	1.230	0.010	0.114	1.182
0	0.738	-0.004	0.028	0.731

Table E.8. Concrete Strain Measurements (NSC-2-South-78)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
0	0	0	0	-1	0	1	-1	0
40	-23	-18	-21	-20	-21	8	-26	-24
83	-45	-34	-40	-41	-41	-11	-51	-44
120	-64	-49	-57	-58	-60	-24	-73	-63
160	-84	-66	-74	-78	-81	-42	-98	-83
199	-106	-81	-93	-96	-101	-63	-123	-104
239	-127	-99	-110	-114	-122	-79	-146	-123
279	-148	-116	-127	-133	-144	-100	-171	-145
320	-170	-134	-147	-155	-166	-116	-197	-167
359	-193	-153	-164	-174	-188	-137	-220	-187
398	-215	-172	-184	-194	-209	-156	-246	-207
420	-232	-189	-197	-207	-223	-170	-261	-219
438	-246	-200	-207	-219	-235	-182	-272	-230
458	-260	-213	-219	-229	-247	-194	-284	-239
478	-278	-226	-234	-244	-262	-242	-301	-254
498	-292	-238	-246	-254	-274	-247	-313	-265
518	-310	-252	-260	-268	-288	-262	-329	-277
539	-327	-268	-272	-282	-305	-262	-345	-289
558	-342	-284	-286	-297	-322	-296	-361	-303
579	-375	-318	-316	-337	-366	-332	-405	-337
599	-419	-361	-357	-396	-430	-377	-454	-378
618	-468	-406	-398	-450	-490	-421	-513	-426
638	-520	-459	-447	-509	-554	-472	-592	-493
657	-565	-506	-487	-562	-613	-512	-656	-545
666	-587	-531	-507	-599	-648	-530	-689	-574
676	-608	-572	-530	-652	-681	-549	-733	-606
686	-638	-602	-557	-678	-718	-573	-783	-641
698	-687	-654	-591	-711	-753	-603	-822	-674
717	-763	-725	-653	-767	-823	-664	-906	-737

Table E.8. Concrete Strain Measurements (NSC-2-South-78)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
725	-794	-755	-681	-799	-860	-695	-947	-768
738	-839	-805	-718	-836	-902	-735	-990	-804
758	-971	-919	-832	-942	-1058	-848	-1141	-922
776	-1054	-1007	-891	-1014	-1138	-909	-1218	-987
780	-1104	-1046	-926	-1056	-1165	-943	-1271	-1087
793	-1220	-1191	-1025	-1188	-1283	-1039	-1400	-1211
799	-1295	-1279	-1085	-1266	-1348	-1098	-1484	-1292
801	-1335	-1328	-1114	-1301	-1383	-1125	-1519	-1322
807	-1446	-1463	-1199	-1397	-1483	-1207	-1624	-1412
812	-1545	-1595	-1280	-1481	-1579	-1286	-1727	-1497
813	-1612	-1683	-1334	-1532	-1643	-1340	-1802	-1548
817	-1643	-1723	-1360	-1560	-1673	-1367	-1835	-1577
818	-1710	-1812	-1420	-1616	-1741	-1429	-1920	-1641
819	-1728	-1835	-1436	-1632	-1759	-1445	-1937	-1659
820	-1821	-1950	-1521	-1733	-1848	-1531	-2045	-1745
827	-1986	-2137	-1660	-1902	-2000	-1698	-2208	-1876
829	-2047	-2220	-1750	-2032	-2080	-1832	-2321	-1930
833	-2097	-2287	-1805	-2101	-2134	-1900	-2383	-1971
832	-2122	-2315	-1822	-2129	-2142	-1931	-2415	-2005
838	-2185	-2419	-1899	-2243	-2233	-2035	-2508	-2073
842	-2248	-2519	-1973	-2351	-2307	-2135	-2582	-2125
841	-2331	-2645	-2063	-2482	-2380	-2292	-2668	-2183
807	-2305	-2640	-2100	-2583	-2381	-2457	-2729	-2169
599	-1873	-2173	-1741	-2221	-2014	-2070	-2341	-1799
397	-1479	-1718	-1401	-1848	-1648	-1696	-1947	-1441
201	-1112	-1293	-1080	-1459	-1296	-1334	-1550	-1092
0	-689	-892	-668	-953	-865	-852	-1010	-695

Table E.9A. End Slip Measurements (NSC-2-South-78)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	25	-23	1500	-17	50	739	-25	-37	-21	-87
40	15	26	24	25	-1480	635	-10	-74	13	249
83	81	11	1008	-13	-814	430	2	-105	13	335
120	79	143	3711	-24	-123	-4	7	-100	-60	358
160	52	7	2905	-54	-400	431	7	-125	-16	255
199	126	129	2964	-78	391	445	45	-107	12	204
239	79	-164	2883	-74	431	424	49	-111	40	180
279	99	170	2786	297	-563	211	64	-192	37	663
320	135	105	913	128	-1243	118	80	-234	122	192
359	116	582	3719	109	-1158	-147	75	-193	-49	833
398	-98	625	3537	-196	-367	29	100	-299	149	838
420	-62	541	3221	-520	205	229	104	-280	-80	559
438	57	516	3993	-272	91	223	112	-290	56	416
458	-19	455	2569	-255	-272	-88	113	-287	-57	-47
478	111	-274	3640	-593	411	87	103	-308	-134	2473
498	204	28	2090	-328	354	331	132	-284	-26	1371
518	216	-127	2788	-645	669	221	109	-250	-6	1205
539	260	-346	-687	-530	1696	163	136	-244	-40	1240
558	-50	-128	-868	-172	1591	-1318	146	-262	-16	1595
579	-248	398	423	-199	2009	-367	141	-287	-61	1287
599	-97	45	-1639	22	2383	-372	135	-275	-218	309
618	-90	53	-180	-426	-529	-299	150	-366	-180	400
638	517	902	-2609	-619	1215	-479	215	-355	119	921
657	129	362	-2337	-357	2391	1037	196	-393	-116	886
666	-250	258	-2551	-691	5017	467	-255	-379	-417	846
676	-189	1110	-2752	-332	4876	92	-276	-462	-418	1205
686	-492	1040	-1769	304	5871	999	-304	-355	-368	702
698	-234	1032	-1467	54	6418	543	-288	-362	-104	736
717	-305	985	-496	2254	9368	3937	-293	-362	414	1939

NOTE: All measurements were multiplied by 10^6

Table E.9A. End Slip Measurements (NSC-2-South-78)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
725	-74	588	-706	3596	11211	4023	-329	-316	681	1937
738	-75	653	-1179	3558	12679	4996	-329	-305	699	2042
758	-859	1060	-506	6959	18768	13096	62	-378	-34	6076
776	1550	1294	-1161	9689	19832	13697	198	364	193	9175
780	1226	400	1366	9711	21414	10208	190	418	119	9418
793	1246	1276	2056	12501	21465	13545	368	342	215	9525
799	1327	689	2503	12529	22330	14035	578	902	78	9524
801	1320	597	3309	12528	22570	13959	551	891	146	9765
807	5470	700	1632	12511	23379	15010	647	1059	47	11799
812	5704	627	100	12467	24156	14979	802	1111	17	12042
813	5977	464	2501	12430	24269	17784	984	1014	-186	12188
817	5977	518	1456	12427	23888	17657	1013	1009	-181	12099
818	6022	927	-593	12432	24413	17603	1351	1111	-140	12073
819	6564	963	-936	12428	24492	17639	1192	1106	-110	12125
820	7016	1018	-3343	12430	25042	16501	1431	1127	-161	14277
827	7309	1381	2749	14833	25794	19522	1731	1552	1672	14170
829	6840	1040	2656	14521	27182	19230	1834	3631	1588	14407
833	7256	927	3523	14707	27811	20549	2176	3625	1602	14284
832	7238	913	2842	14688	27762	20689	2192	3639	1615	14349
838	7296	886	1059	14712	27501	20613	2539	3635	1629	15454
842	7372	900	1255	14708	27099	20879	2577	3624	1345	14652
841	7548	787	2021	14717	27162	21763	2600	3571	3919	14792
807	7692	700	1092	14561	27268	21319	3097	3521	4119	15915
599	7454	1012	1421	15086	27370	21828	4179	3520	6631	17387
397	7647	969	2590	15277	27168	21769	4302	3582	6308	16785
201	8276	1288	733	15707	27216	21795	4328	3694	6322	17514
0	9042	6590	5881	16465	27058	20420	8690	9988	12138	19570

NOTE: All measurements were multiplied by 10^6

Table E.9B. End Slip Measurements (NSC-2-South-78)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	East	West	East	West
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	-100	-83	-4	6	-45	-73	-30	-423	-75	-5
40	32	4	-14	-7	38	-16	-25	-12	4	-1
83	93	19	-11	28	-32	154	-30	87	-54	-10
120	228	-144	0	99	-43	330	-17	-1357	-27	3
160	50	-471	-11	94	-114	320	-97	-1443	427	5
199	672	-583	-23	7074	-90	482	-121	-1414	385	5
239	690	-77	-41	7099	-111	501	-135	-1430	382	-9
279	671	-301	-19	7087	-94	661	-144	-1376	399	-14
320	415	-468	-7	7079	-79	636	-106	-1371	454	10
359	318	-463	-35	7057	-128	619	-121	-1442	405	-7
398	618	-475	-7	7075	-98	465	-128	-1435	397	32
420	682	-231	-31	7049	-88	441	-172	-1443	439	24
438	576	-144	-38	7095	-98	566	-184	-1426	436	3
458	575	-517	-52	7092	-73	333	-199	-1427	393	-2
478	880	280	-23	7234	3	951	-202	-1416	482	12
498	924	-463	-16	7290	51	2417	-200	-1362	603	14
518	991	-47	3	7484	168	2512	-200	-1416	496	18
539	334	1087	39	8667	550	2923	-232	-1407	432	5
558	1086	447	289	9172	905	3228	-234	-1390	520	21
579	-216	1069	668	9952	1360	4312	-266	-1373	558	17
599	-686	3914	1005	11524	2150	7630	-648	-1223	739	27
618	-828	4766	1532	11209	3126	8585	-665	-1204	755	36
638	-383	5800	2916	13945	4682	10650	-638	-1277	709	35
657	11	7209	6668	15578	5332	13054	-689	-1289	541	40
666	919	7142	8349	16582	6131	13638	-647	-1351	811	36
676	1240	7347	9035	17432	6308	14029	-596	-1281	636	33
686	2416	7687	11310	19355	6871	15183	-562	-1313	1107	26
698	3563	10109	12568	19737	7513	16219	-584	-1307	1005	35
717	5447	12985	16290	9170	10276	19054	-664	-1355	1933	50

NOTE: All measurements were multiplied by 10^6

Table E.9B. End Slip Measurements (NSC-2-South-78)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	East	West	East	West
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
725	7166	13716	17716	10734	11152	20557	-682	-1442	1523	46
738	8241	14465	19082	11512	11997	21798	-675	-1447	1494	40
758	11676	18310	23996	17529	18741	26841	-901	-1721	2002	54
776	12696	19069	24559	17606	20872	28541	-918	-1188	1635	47
780	13181	20325	25537	18832	22146	29834	-846	-1551	1356	63
793	14370	22280	26665	19434	22352	33722	-930	-1115	1260	69
799	15034	22496	27406	22454	23005	34727	-909	-1198	1293	68
801	15399	22791	27652	22886	23299	34785	-925	-1275	1463	65
807	15770	22823	28484	25801	23953	37079	-935	-1536	1678	66
812	16121	23957	28940	26725	25980	37475	-929	-1754	1537	62
813	16124	24108	29306	27410	25654	37830	-908	-1675	1253	47
817	16549	24767	29544	27505	25800	38029	-919	-1648	1316	58
818	16889	23965	29982	27512	25624	38467	-949	-1692	1472	57
819	17032	24444	30159	27502	25550	38738	-949	-1711	1496	55
820	17363	25187	30846	26291	25350	40531	-1042	-1893	946	55
827	18105	25221	31836	24980	27722	43213	-948	-1341	525	50
829	18204	25605	32321	25717	28457	44855	-1049	-1275	514	37
833	18284	26037	32984	26062	28810	46200	-980	-1335	189	23
832	18312	25816	33085	26303	29179	46382	-974	-1359	207	22
838	18342	26356	33369	26641	29482	47079	-1175	-1455	135	40
842	18515	26762	33530	27176	29506	47761	-1081	-1467	226	22
841	18514	26463	33784	27639	29901	49007	-1086	-1380	453	17
807	19230	26380	34289	28169	31604	49703	-1038	-2391	918	-1
599	19603	26329	34316	30412	31579	49600	-1073	-2316	1035	12
397	19259	26369	34288	30415	31632	49578	-1108	-2411	501	8
201	18901	26595	34329	30673	32198	49555	-1098	-2357	481	26
0	19471	26911	34721	31341	32800	49641	-960	-2150	560	11

NOTE: All measurements were multiplied by 10^6

Table E.10. Deflection Measurements (NSC-2-North-72)

Applied Load (kips)	Max Deflection (in)	Avg North Deflection (in)	Avg South Deflection (in)	Max Net Deflection (in)
0	0.000	-0.001	0.000	0.001
42	0.044	0.037	0.000	0.020
81	0.068	0.051	0.001	0.034
120	0.092	0.061	0.004	0.051
160	0.113	0.070	0.006	0.066
200	0.131	0.078	0.007	0.078
241	0.154	0.085	0.010	0.095
280	0.168	0.092	0.012	0.104
320	0.181	0.099	0.015	0.111
360	0.203	0.106	0.017	0.128
400	0.224	0.112	0.020	0.144
440	0.242	0.118	0.022	0.157
460	0.253	0.124	0.025	0.164
480	0.263	0.126	0.026	0.173
500	0.276	0.129	0.027	0.183
521	0.289	0.132	0.028	0.194
540	0.300	0.131	0.029	0.205
560	0.312	0.134	0.031	0.214
579	0.328	0.139	0.032	0.227
599	0.349	0.142	0.034	0.245
638	0.425	0.149	0.036	0.315
658	0.469	0.149	0.038	0.359
680	0.525	0.153	0.039	0.412
699	0.575	0.156	0.040	0.459
719	0.639	0.159	0.042	0.521
739	0.704	0.162	0.043	0.584
760	0.782	0.166	0.044	0.659
780	0.859	0.168	0.045	0.734
798	0.948	0.174	0.046	0.819

Table E.10. Deflection Measurements (NSC-2-North-72)

Applied Load (kips)	Max Deflection (in)	Avg North Deflection (in)	Avg South Deflection (in)	Max Net Deflection (in)
813	1.023	0.176	0.047	0.892
820	1.074	0.177	0.047	0.943
830	1.144	0.179	0.047	1.011
835	1.187	0.179	0.047	1.054
843	1.302	0.181	0.048	1.167
846	1.403	0.183	0.048	1.267
854	1.503	0.184	0.048	1.367
857	1.574	0.184	0.048	1.438
859	1.608	0.184	0.049	1.471
862	1.706	0.185	0.049	1.568
865	1.801	0.188	0.049	1.662
871	1.899	0.189	0.049	1.759
871	1.971	0.189	0.049	1.831
215	1.913	-0.030	0.019	1.926
0	0.918	-0.145	0.008	1.009

Table E.11. Concrete Strain Measurements (NSC-2-North-72)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
0	1	2	-1	0	1	8	0	1
42	-26	-22	-20	-20	-17	-9	-24	-21
81	-49	-44	-37	-37	-35	-36	-44	-39
120	-72	-64	-52	-54	-52	-70	-66	-58
160	-95	-86	-68	-73	-70	-86	-89	-76
200	-119	-111	-86	-91	-89	-110	-111	-96
241	-144	-132	-103	-110	-106	-112	-135	-114
280	-168	-156	-119	-128	-125	-142	-155	-132
320	-193	-180	-137	-147	-142	-161	-179	-153
360	-218	-203	-154	-165	-161	-189	-201	-171
400	-252	-236	-174	-186	-183	-187	-224	-192
440	-285	-268	-198	-207	-204	-231	-248	-213
460	-303	-281	-211	-220	-215	-226	-260	-224
480	-319	-297	-221	-230	-227	-256	-272	-237
500	-337	-313	-234	-243	-238	-189	-285	-246
521	-352	-329	-244	-255	-250	-251	-297	-259
540	-367	-343	-256	-266	-262	-303	-310	-270
560	-386	-360	-267	-278	-273	-289	-323	-281
579	-407	-381	-277	-296	-290	-337	-339	-292
599	-444	-415	-303	-329	-321	-350	-363	-312
638	-536	-497	-379	-433	-420	-460	-471	-411
658	-594	-552	-420	-482	-469	-492	-531	-460
680	-662	-620	-468	-541	-523	-529	-596	-517
699	-712	-672	-501	-594	-568	-568	-653	-566
719	-855	-740	-538	-664	-620	-555	-730	-630
739	-986	-806	-582	-727	-670	-651	-791	-690
760	-1118	-893	-641	-797	-729	-700	-871	-756
780	-1248	-975	-699	-872	-792	-802	-952	-826
798	-1326	-1069	-765	-959	-864	-884	-1040	-907

Table E.11. Concrete Strain Measurements (NSC-2-North-72)

Strain at Top of Concrete Slab x10-6								
Load	Row 1 (North)		Row 2 (Middle)				Row 3 (South)	
(kips)	West	East	West			East	West	East
813	-1392	-1154	-820	-1038	-926	-919	-1110	-972
820	-1428	-1206	-851	-1080	-963	-957	-1148	-1006
830	-1473	-1290	-900	-1161	-1025	-1027	-1208	-1062
835	-1504	-1339	-928	-1204	-1061	-1059	-1239	-1091
843	-1618	-1494	-1006	-1333	-1160	-1158	-1319	-1165
846	-1728	-1648	-1083	-1443	-1260	-1250	-1390	-1233
854	-1803	-1795	-1161	-1540	-1359	-1311	-1480	-1317
857	-1861	-1932	-1203	-1594	-1481	-1342	-1550	-1373
859	-1889	-2016	-1219	-1618	-1524	-1361	-1580	-1398
862	-1982	-2246	-1285	-1704	-1652	-1448	-1679	-1451
865	-2059	-2445	-1357	-1785	-1766	-1523	-1769	-1514
871	-2132	-2606	-1422	-1857	-1842	-1573	-1843	-1577
871	-2113	-2724	-1450	-1896	-1889	-1645	-1874	-1597
215	-1730	-1846	-926	-717	-737	-828	-560	-478
0	-901	-993	-424	-408	-438	-405	-326	-312

Table E.12A. End Slip Measurements (NSC-2-North-72)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	15	-100	-303	-161	237	-1534	-1	-6	75	-67
42	-14	182	92	41	284	-659	7	-40	38	-45
81	-282	217	-959	10	927	144	-19	-144	-86	-67
120	-118	439	-835	-71	-2041	-224	-70	-82	-83	-136
160	376	363	-926	-41	-2312	47	-128	-122	-160	-625
200	81	136	-377	-79	-715	310	-146	-122	-213	-633
241	128	179	-1329	-120	-712	-1184	-237	-136	-268	-310
280	578	81	-1320	-160	158	233	-246	-155	-137	-293
320	171	192	-1182	-77	411	856	-166	-204	-137	-217
360	292	71	-1462	-91	616	935	-172	-182	-191	-94
400	463	99	-1578	-242	819	759	-262	-208	-223	123
440	182	-179	-2292	-426	1451	600	-283	-154	-75	204
460	-12	-694	-5801	-928	1298	-981	-224	-57	-72	117
480	-17	-767	-8089	-973	1509	-1226	-202	-26	-18	19
500	47	-195	-3631	-1099	1318	848	-122	-83	-55	-106
521	73	-171	-4153	-981	-1215	-530	-130	-72	26	-81
540	182	-491	-3847	-1047	-1621	-1324	-150	-148	13	-121
560	168	-247	-2651	-1004	-1303	751	-185	-166	69	-148
579	1373	87	-3905	-364	-1253	3829	50	43	14	232
599	1611	327	-3850	-495	-593	3604	-188	32	-632	66
638	1602	1144	-3662	-246	1265	3266	-386	-105	200	1274
658	319	573	-5445	-326	2657	4617	-490	-80	-55	1177
680	3305	652	-2747	-231	1141	7425	-454	-20	125	998
699	3149	496	-3394	-232	3271	10568	-823	30	190	1843
719	8272	383	597	1025	5555	11237	-610	243	-44	1951
739	9018	211	1628	1328	6350	13358	-793	295	-132	1762
760	11236	166	-2246	1703	10976	18346	-673	288	-103	2511
780	11192	31	-1658	9866	11182	22083	-681	12	-6	3793
798	11928	37	-405	9956	16402	23641	-548	-39	-186	4880

NOTE: All measurements were multiplied by 10^6

Table E.12A. End Slip Measurements (NSC-2-North-72)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Load	West	Bottom Flange								East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
813	14471	360	2210	9936	16983	25304	445	-154	-68	6003
820	14420	293	1921	9948	17088	24625	447	-166	-233	5872
830	19842	186	2839	9819	19980	27655	2737	-76	-10	8824
835	19925	127	3265	9953	20003	28479	2505	-41	-51	8893
843	19800	-72	2838	9834	28146	32348	3647	50	-171	10743
846	19651	-141	4785	9910	27403	31677	3644	37	-238	10595
854	19714	-156	5427	10050	28357	31658	3671	4	-213	12203
857	20444	76	3177	10221	27620	32062	5342	-9	-519	12026
859	20430	59	3441	10254	27777	30549	5271	23	-469	12140
862	20091	-131	4296	10084	27837	32336	5370	-140	-666	14016
865	20862	-112	5101	10294	27507	35784	8450	212	-637	14900
871	20474	46	5955	10376	28096	36154	8367	262	-664	14310
871	29012	-384	3692	21787	32387	35265	10048	2817	-599	17306
215	173768	138230	145594	161705	171771	178938	168786	121789	99896	134888
0	154233	113206	116067	131696	139627	146995	134174	97901	98486	129927

NOTE: All measurements were multiplied by 10^6

Table E.12B. End Slip Measurements (NSC-2-North-72)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	West	East	West	East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
0	133	-23	18	475	24	0	13	313	-48	23
42	39	-8	2	857	-6	13	8	530	-4	4
81	89	17	-1	1096	22	20	-5	1024	-62	-2
120	151	29	7	1341	2	39	-10	935	-32	24
160	-53	16	11	339	16	34	-19	1066	-20	14
200	95	38	-6	867	3	39	-8	1100	3	10
241	-49	39	11	1282	-41	46	-7	1094	-14	18
280	-22	-5	11	1626	-26	54	-1	1148	9	17
320	79	4	6	2219	-56	49	-39	1207	45	22
360	105	22	-4	2730	-63	44	-44	1229	24	36
400	60	44	-2	4551	-79	65	-60	1398	18	32
440	24	7	-4	7736	-50	59	-7	1523	27	32
460	467	31	-37	-2897	115	140	-46	1832	30	9
480	492	100	-21	-2809	89	8	-67	1772	55	29
500	227	181	-61	-2520	89	56	-105	1791	54	13
521	296	271	-85	-3431	86	73	-76	1854	71	27
540	361	323	-91	-2481	146	36	-110	2058	24	41
560	676	335	306	-1521	157	33	-107	1976	25	24
579	-581	380	2906	-206	163	0	-160	1143	263	142
599	-623	410	4511	1487	-11	-33	-32	896	1340	64
638	0	261	8978	-5699	333	427	38	-16437	2152	-112
658	558	285	11029	-3928	540	749	68	-16345	2257	-148
680	2611	333	12858	-1152	1532	1505	-7	-14031	2224	-198
699	3180	275	14600	1576	2309	2693	-39	-17164	2097	-203
719	4919	338	17450	4388	4230	5574	-46	-17058	2084	-263
739	7701	316	20041	7965	6453	7578	-12	-17014	2115	-249
760	9705	7745	24178	11902	9578	9128	-36	-16261	2371	-287
780	14203	7448	28673	15601	10714	12280	-139	-16572	2305	-271
798	16093	7183	33062	20082	18317	15863	-98	-16674	2368	-276

NOTE: All measurements were multiplied by 10^6

Table E.12B. (Cont) End Slip Measurements (NSC-2-North-72)

	B1	B2	B3	B4	B5	B6	C1	C2	D1	D2
Load	West	Bottom Flange				East	West	East	West	East
(kips)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)	(in)
813	20351	7328	36137	23326	18965	18241	-141	-15552	2384	-262
820	20336	7345	36177	24003	18946	19191	-166	-15563	2374	-289
830	23501	8155	38106	25198	18820	21064	-137	-16628	2471	-281
835	23322	8260	39431	26025	18828	21655	-150	-16629	2490	-266
843	26381	8074	40651	28889	20067	23534	-129	-16570	2654	-262
846	27711	8222	42994	30276	20152	25210	-120	-16467	2753	-256
854	29856	8309	43248	31696	20155	26021	-141	-16539	2770	-282
857	33716	17050	46130	33497	27348	27406	-158	-15645	3047	-283
859	33634	17051	46191	33568	27347	27422	-166	-15660	3035	-326
862	35505	17065	47815	34604	27336	28339	-154	-15675	2577	-265
865	36479	17348	49338	34905	27434	29296	-132	-15705	2952	-210
871	39388	17094	50210	36703	27408	29455	-129	-15723	2680	-177
871	44337	17209	55275	40645	27559	32139	-123	-15383	2539	-257
215	331480	------	550146	567584	774911	838588	1151	-19034	9410	2092
0	309418	------	562273	604559	799067	838530	6300	-17407	11505	3291

NOTE: All measurements were multiplied by 10^6

APPENDIX F

NOTATION

A_{strand} Area of prestressing strand

B Bond stress factor used in transfer length equation [6]

d_b Diameter of prestressing strand

E_c Modulus of elasticity of concrete

E_{ci} Modulus of elasticity of concrete at transfer

E_{ps} Modulus of elasticity of prestressing strand

f_c Stress in concrete

f_{ps} Stress in strands at failure

f_{pu} Ultimate tensile strength of strands

f_{se} Stress in strands after losses

f_{si} Stress in strands immediately before transfer

f'_c Concrete compressive strength at 28 days

f'_{ci} Concrete compressive strength at transfer

L_b Length of debonding for debonded strands

L_d Development length of prestressing strands

L_e Embedment length of prestressing strands

L_t Transfer length of prestressing strands

M_{cr} Cracking moment for cross section

M_{test} Maximum total moment acting on cross-section during testing

M_u Moment capacity of cross-section

U'_d Strand surface coefficient used in development length equation [6]

U'_t Strand surface coefficient used in transfer length equation [6]

β_1 Depth of equivalent rectangular stress block / Depth of neutral axis

ε_{se} Strain in strands after losses (due to prestressing only)

ε_{si}	Strain in strands immediately before transfer
λ	Multiplying factor applied to flexural bond length
ω_p	Reinforcement index

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