BOND BEHAVIOR OF 0.6-INCH DIAMETER PRESTRESSING STRAND

AT TWO INCH GRID SPACING IN FULLY BONDED

HIGH STRENGTH AND NORMAL STRENGTH

COMPOSITE TEXAS TYPE C BEAMS

APPROVED BY THE

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by

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Analbhai N. Shah
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CHAPTER ONE

INTRODUCTION

1.1 Background Information

Prestressed concrete beams are frequently used in the construction of bridges. In the past several years, there have been many major research projects in the field of prestressed concrete. It is very important to use efficient prestressed concrete members so that economy can be achieved.

It has been a continuous interest of researchers to take more and more benefit of prestressing force while using the same standard cross sections on increasingly longer spans. The objective of applying more prestress force can be achieved by using larger diameter strand. The prestressed industry started with 5/16 in. diameter strand but 3/8 in. and ½ in. diameter strands have been successfully developed and used in the industry. Concrete strength has also steadily increased in practice, moving from 5000 psi to 10000 psi for some designs.

In the past, it was very common to use 0.5 in. diameter strand in the pretensioned concrete industry. A recent development is the use of 0.6 in. diameter strand instead of 0.5 in. strand. The use of 0.6 in. strand can lead to about 40% larger capacity than 0.5 in. strand. This is simply because of the 40% higher area of 0.6 in. strand than that of 0.5 in. strand. This will lead to a smaller number of strands required to achieve the same prestressing force in the member or alternatively, more prestressing force can be applied to the member having the same number of strands. This will definitely result in the use of longer beam span length or larger beam spacing for a given span which will eventually lead to economical structures.

However, the use of 0.6 in. strand in the precast prestressed concrete industry is not that common. It is very important to decide whether current code requirements can be used or modifications are required to use 0.6 in. strands. The surface area of 0.6 in. strand is only 20% higher than that of 0.5 in. strand. Thus, the bond forces act on an area 20% larger and the pretensioned force is about 40% higher. It is to be noted that greater prestress force will require greater bond stress for anchorage. It is important to understand bond behavior of 0.6 in. diameter strands before they can be accepted in usual practice.

The use of high strength concrete has resulted in more durable and impermeable concrete structures. The use of high strength beams can lead to larger beam spacing and longer span length in bridge construction but higher prestress force is needed utilizing 0.6 in. strands. The same standard cross section for the beams can be used by using high strength concrete. The advantages from the use of high strength concrete can be achieved by the use of larger diameter strands.

1.2 Objectives of Research Program

The primary objective of the research is to investigate transfer length, development length and bond behavior of full scale Texas Type C composite beams which utilize 0.6 inch strands at 2 inch grid spacing. The project is part of a major research project associated with a San Angelo, TX bridge project which has very long spans with very high strength concrete. This test program was conducted at Ferguson Structural Engineering Laboratory at The University of Texas at Austin. Both normal strength concrete and high strength concrete girders with a normal strength slab were tested.

1.3 Objectives of this Study

The purpose of this test program is to measure transfer length, development length and to observe bond behavior of 0.6 inch strands spaced at 2 inch grid spacing in four Texas Type C composite girders. Two high strength and two normal strength full scale girders were fabricated in the prestressing plant at Victoria, TX, and deck slabs were added in the Phil M. Ferguson Laboratory to complete the composite beams which were tested.

Transfer length was measured at the time of transfer of prestressing force for the Type C (I-shaped) beams in Victoria, TX. In order to approximate development length, several tests were conducted with different embedment lengths. In all the tests, instrumentation was provided to measure end slip of each strand during the test.

1.4 Organization of Report

Chapter one of the report gives an introduction and states the objectives of the study. Chapter two furnishes theoretical information on transfer length, development length, bond behavior and previous research conducted in this area. Chapter three focuses on the experimental work done for this research. Chapter four presents data obtained from the experiments and chapter five gives conclusions which can be made from these tests of four beams.

CHAPTER TWO

LITERATURE OVERVIEW

2.1 Introduction

This chapter will include brief descriptions of development length, transfer length, and bond mechanism in prestressed concrete members. Previous experimental work related to measurement of end slip of strands will be presented.

2.2 Transfer Length

Transfer length is defined as the length required to transfer effective prestress force from strands to concrete. The steel stress varies from zero at the end of the member to full effective prestress at the end of the transfer length zone.

ACI[2] Section 12.9 gives formulae for transfer length. The suggested formula for transfer length is:

$$L_t = (f_{se}/3)\ d_b$$

Figure 2.1 is a graphic presentation of the transfer length and development length given in the ACI building code.

The ACI code suggests that the transfer length is approximately 50 times the diameter of strands. In current code provisions given by ACI and AASHTO, transfer length is not a function of concrete strength. However, Castrodale, Kreger and Burns [3] suggested that the higher the concrete strength, the lower the transfer length. Russell and Burns [12] investigated the influence of strand diameter, strand spacing, debonding of strands, specimen size and concrete strength on transfer length.

Transfer length is an important property to maintain integrity of the structure. It has a prominent effect on the cracking load. It has been found that if cracks occur within the transfer length of a member, the bond stress becomes very high and the strands may slip.

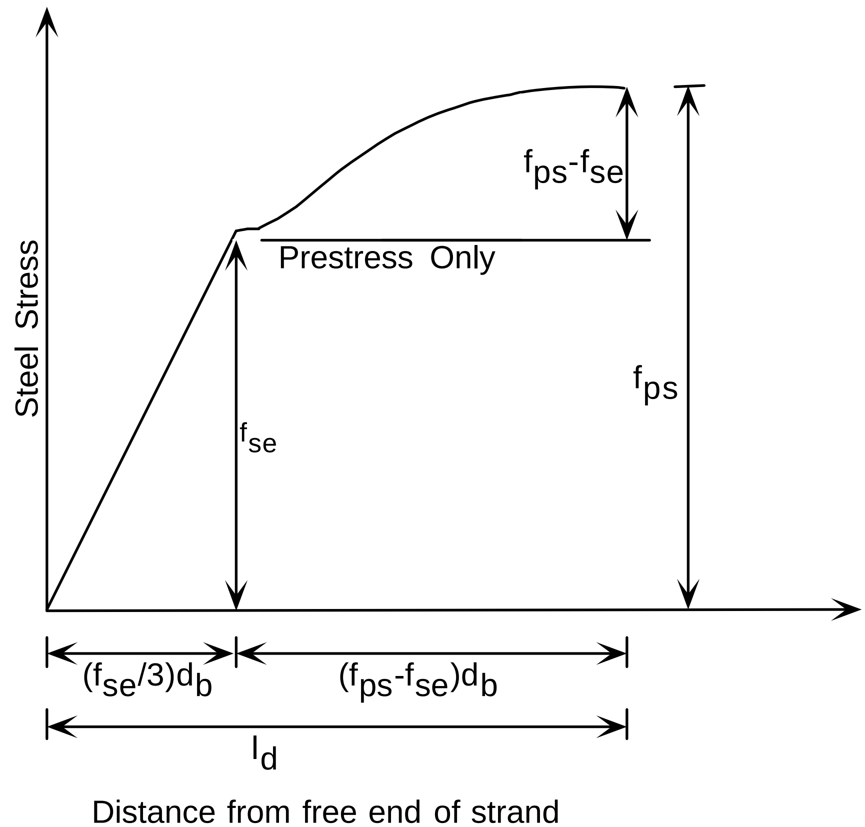

Figure 2.1 Variation of steel stress with distance from free end of strand [2]

2.3 Flexural Bond Length

Externally applied loads cause tension in the strands and result in very high ultimate stress in the strands. Flexural bond length is the bond length required to reach ultimate stress f_{ps} from effective prestress stress f_{se} as shown in Figure 2.1. After cracking, flexural bond stress between the steel and concrete is responsible for allowing the increase in steel stress above the effective prestress.

2.4 Development Length

External loads acting on the member induce tension in the strands and the diameter of the strand will reduce because of the poisson's ratio. This tension in the steel strands is resisted by bond stress between strand and concrete. Development length is the bond length required to resist tension developed by both prestress force and externally applied loads. Development length defines the border between flexural failure and bond failure.

Embedment length is the bond length between the end of the member and the maximum moment section. It should be noted that if embedment length is more than development length then flexural failure will occur, and if embedment length is less than development length then bond failure will occur.

The ACI code gives the following equation for development length for three or seven wire strands.

$$l_d = (f_{ps} - 2/3 f_{se}) d_b$$

Mathematically, development length is the sum of transfer length and flexural bond length as shown in Figure 2.1.

2.5 Bond Mechanism

It is very important to understand the transfer of forces from steel to concrete by bond mechanism. In general, bond failure is progressive rather than instantaneous. In the past, several researchers tried to express bond mechanism empirically but, current code provisions do not suggest any formulae for bond stress values.

Pettie and Pope [10] have explained that bond between steel and concrete is because of the shrinkage of the concrete. Bond effect is mainly influenced by shrinkage of the concrete closely adjacent to the steel. The hardening of concrete is an exothermic process and concrete at the center of a specimen will have a higher temperature. Concrete at the middle will harden more rapidly and will result in rapid development of bond. It is found that growth of the bond is higher than that of concrete strength.

Bond consists of mainly three mechanism:

1. Adhesion
2. Hoyer's effect or wedge action

3. Mechanical Interlocking

2.5.1 Adhesion

Adhesion is the bond between two different materials such as concrete and steel. Adhesion keeps both steel and concrete intact. When tension in the strand increases because of applied loads, adhesion between strand and concrete tries to prevent slip of the strands. Strand slip occurs when adhesion is lost.

2.5.2 Hoyer's Effect

Hoyer investigated bond behavior and developed a theory called hoyer's effect. Hoyer's effect can be described as follows.

In pretensioned members when prestressing strand is tensioned, its diameter will reduce because of the poisson's ratio. Concrete is then poured to cast the member. Prestressing force is released after concrete has gained enough strength. Upon the release of prestressing force, strands will try to regain their original shape but surrounding concrete will resist expansion of strands. Thus normal force is provided by concrete acting on the strands and it will develop its horizontal component-frictional force. The horizontal frictional component will anchor the strand within the concrete and will try to prevent slippage of the strands upon loading. This phenomenon is also known as the wedge action.

When the pretensioned member is loaded by external loads, additional tension will be developed in the strands and diameter of the strand will decrease because of poisson's ratio. Consequently hoyer's effect will be diminished and effective prestress force will also be reduced. If the strands slip, the horizontal component of wedge action is not sufficient to hold both concrete and steel together.

Wedge action is very predominant in the transfer zone and hence if cracks occur in the transfer zone, hoyer's effect will be reduced and bond failure will likely occur. Hoyer's effect is shown in Figure 2.2.

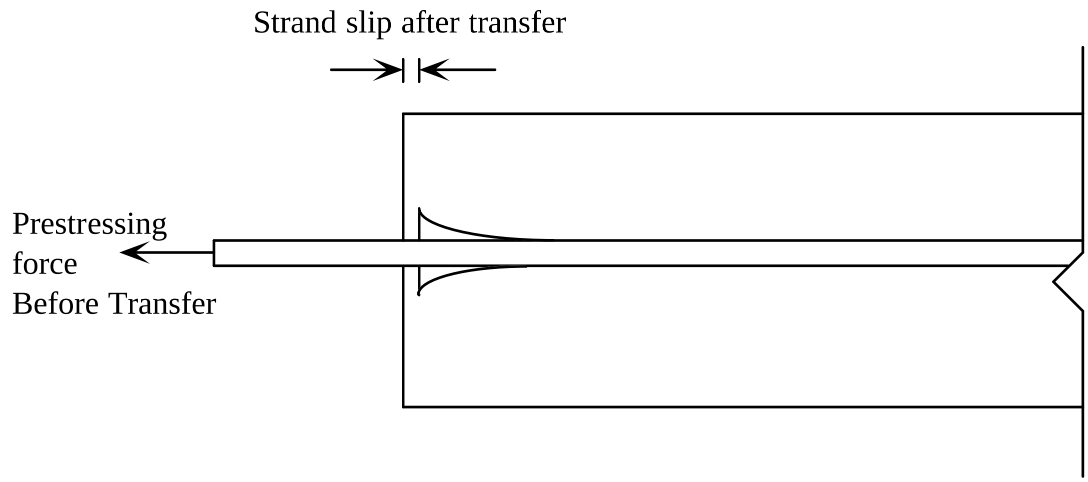

Figure 2.2 Transfer of prestress [8]

2.5.3 Mechanical Interlocking

When concrete is placed, concrete will fill all the space around helical seven wire strand. The helical shape of the strand will provide enough mechanical resistance to resist additional load even after end slip of the strands at the ends. Mechanical interlock between strand and concrete will also prevent the strand from pulling out without twisting.

It should be noted that good bond behavior is necessary to prevent end slip of the strands. However, a small amount of strand slip occurs at transfer of prestress and also before a general bond failure.

2.5.4 Causes of Poor Bond

The factors which cause poor bond behavior are low strength concrete, sudden release of prestress, oily surface of strands, and poor consolidation of concrete around the strands. Bond failure may occur due to too close spacing of the strands. Rusch [11] noted that bond strength obtained from tests depends on the rate of loading.

2.6 Previous Research

The development of strand with larger diameter is an interesting topic for researchers. The prestress industry started with 5/16 in. strand diameter and then researchers developed 3/8 in. and ½ in. diameter strands. Investigation of development length, transfer length and bond behavior are the prime concerns when testing members with larger strand diameter.

2.6.1 Hanson and Kaar [5] - PCA Laboratory (1959)

Hanson and Kaar investigated flexural bond behavior of pretensioned beams by using 1/4, 3/8, and ½ inch diameter strands. The main objectives of the tests were to study bond behavior and bond slip of the pretensioned strand. Primary variables in the test series were strand diameter and embedment length. Other variables such as different steel percentages, concrete strength, surface condition of strands and embedded end anchorages were included in the research program.

Forty seven beams were tested at the PCA laboratory. These beams were tested with different strand size and embedment length. Some of the beams were tested with a point load at midspan and others were tested with two point loading. General bond slip occurred when the flexural bond stress wave reached the transfer zone. Hanson and Kaar developed design curves from their data to give guidance to prevent bond slip. It is obvious that the increase in steel stress is responsible for strand slip.

2.6.3 David Yankelevsky [14] - Israel Institute of Technology (1965)

To measure bond-slip behavior, finite element analysis was developed by Yankelevsky. A one dimensional model was developed to describe axial force in a steel bar and slip relation. In this method, the steel bar and concrete surface were divided into a number of finite elements. The interface of the bar and concrete was modeled by springs. The stiffness matrix was developed to relate end slip and force in the bar for the small element. Stiffness matrices of all finite elements were arranged to make the global stiffness matrix and an iterative process was used to find the exact amount of slip.

The model developed by Yankelevsky gave results which agreed with measured data. The advantage of this method lies in the fact that it is easy to use in analysis once it is developed.

2.6.4 Arthur Anderson and Richard Anderson [1] - (1976)

Thirty six pretensioned hollow core units were tested to investigate flexural bond behavior. Hollow core slab units were taken from factory production and load was applied at the middle of the slabs. Tests were conducted using three different types of slab units. Some tests were conducted with oiled strands to see the impact of oiled strands.

It is known that strand slip occurs when the prestressing force is released. This free end slip plays an important role in the behavior of members. It was noted that the strand with the highest free strand slip showed maximum end slip at the end of the tests. It was noted that the strands with oiled surface slipped more than the strands with clean surface. It was noted that specimens with inadequate consolidation resulted in higher free end slip and early bond failure. Poor consolidation results in the formation of voids around strands; voids collapse upon loading, and strand slip occurs. Thus, proper vibration is required to achieve good consolidation and adequate bond.

2.6.4 Russell and Burns [12] - The University of Texas at Austin (1993)

The test program was conducted to study transfer length, development length and bond behavior. A total of 28 development tests were conducted with 19 AASHTO-type I girders and 9 rectangular beams. Russell and Burns used both 0.5 in. and 0.6 in. diameter strands in their research program. The effect on transfer length by using different strand diameter, strand spacing, size of cross section, debonding of strands, strand surface condition and confining reinforcement was investigated.

The average transfer length measured was 30 inches for 0.5 in. diameter strands and 40.9 in. for 0.6 inch strand diameter. The development length for 0.5 inch strands used in AASHTO- type I beams was 72 inches and that for 0.6 inch strand was 84 inches.

Three full scale Texas Type C girders with 1/2 inch diameter strands and a cast in place composite deck were also tested. Two of the three beams were designed with debonded strands and the third one was designed with fully bonded draped strands.

Minor end slips occurred in all of the three specimens. The largest end slip measured was 0.080 inches. The largest end slip was measured in the beam with draped strands. Russell and Burns concluded that girders with debonded strands showed the same behavior as that of beams with draped strands.

2.6.5 Shawn Gross and Burns [4] - The University of Texas at Austin (1994)

The experimental program was conducted at the Phil M. Ferguson Structural Laboratory. Two high strength rectangular beams were cast using 0.6 inch diameter strand. The objective of this research work was to measure transfer and development length. The beams used were 14 inches wide and 42 inches deep with six 0.6 in. strands spaced at two inches on center at the bottom. Three #9 bars were added at the top of the beams. Concrete strength was about 11800 psi at 28 days.

Gross reported a transfer length of about 14.3 inches for the 0.6 in. diameter strands of rusty surface condition. This value is conservative compared to the value given by ACI and AASHTO code provisions. Determination of development length is an iterative process. Tests were conducted using embedment lengths of 163 in., 119 in., 102 in., and 78 inches. In all four tests the failure mode was flexural and hence development length was shown to be less than 78 inches. The average concrete strain at the top at the time of ultimate load was 0.0024, and steel strain at ultimate moment was 3.78%. Maximum end slip recorded was 0.003 in., with embedment length of 78 inches.

CHAPTER THREE

EXPERIMENTAL PROGRAM

3.1 Introduction

Experiments have been conducted using full scale Texas Type C composite girders. Two high strength and two normal strength girders were cast in the prestressing plant at Victoria, TX and composite slabs were cast at the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas at Austin. Test specimens were instrumented to measure end slip, deflection of beam and concrete strain at top of the slab. The test on each end of each beam was conducted with different embedment length as described in this chapter.

This chapter includes information on specimen details, material properties, construction of the composite beam, loading frame set up, and instrumentation used during testing.

3.2 Test Specimens

Texas Type C beams were designed and detailed according to requirements of the Texas Department of Transportation who funded this project. It should be noted that Texas Type C beams comprise approximately 1/3 of the pretensioned concrete beams used in bridge design in Texas. This particular section was used as part of the research program for a bridge project in San Angelo, Texas, the North Concho River Bridge.

Four fully bonded test girders were cast at the prestressing plant. The test beams had 20 prestressing strands; the bottom flange had 10 strands in the first row and 6 strands in the second row from the bottom. Four strands were used in the top flange to keep the stresses within allowable limits at transfer. A two inch grid spacing was used for the arrangement of the strands as shown in Figure 3.1. High strength beams were 52 feet long and normal strength beams were 54 feet long. The test beams had vertical stirrups consisting of 2-#4's @4" spacing to serve as shear reinforcement. The objective which was kept in mind while designing the shear reinforcement was to avoid brittle shear failure. Strand slip and thus bond behavior was investigated without fear of shear failure for each test beam.

Neoprene pads used at supports were reinforced with steel plates. Three beam support pedestals for each beam were cast at the laboratory. Neoprene pads were used to provide bearing area for the beams as shown later in Figure 3.4.

The deck slab used was 7.5” thick and 72” wide. Longitudinal reinforcement consisted of #4’s @12” both top and bottom. Six #4 bars were used as longitudinal reinforcement both top and bottom and transverse reinforcement consisted of #4’s @ 12” as shown in Figure 3.1.

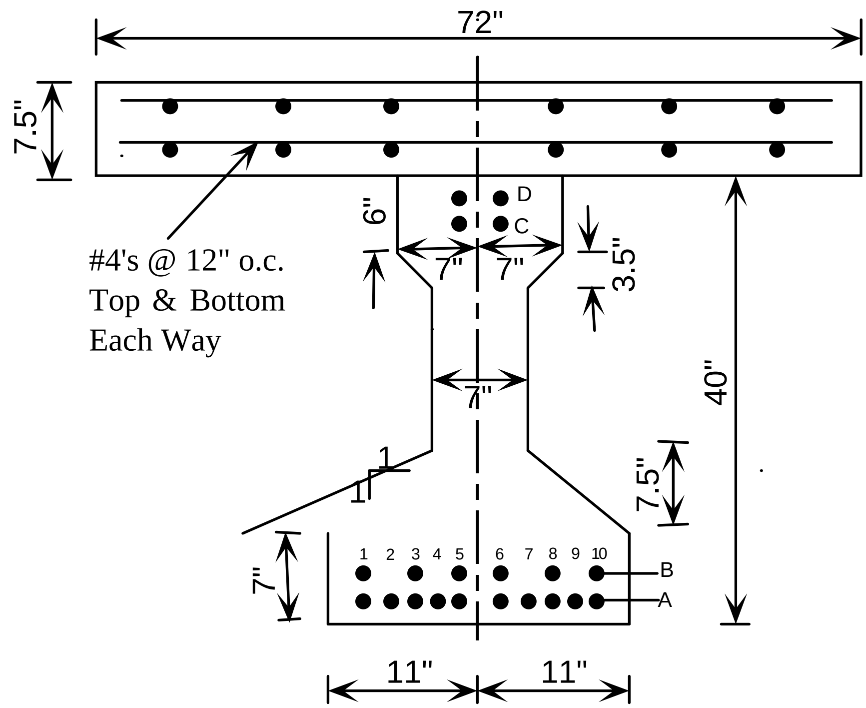

Figure 3.1 Texas Type C Girder With Composite Deck

3.3 Material Properties

Concrete strength and modulus of elasticity tests using 4”X8” cylinders were conducted at The University of Texas at Austin. Strands were also tested to determine their stress-strain response and ultimate capacity for 0.6 inch diameter 270 ksi grade low relaxation strand.

3.3.1 Concrete

The test beams were cast with two different concrete strengths. Two beams were of normal concrete strength (NSC) and the other two beams were of high strength concrete (HSC). Concrete cylinders were prepared at the time of casting the beams in the prestressing plant in Victoria, TX. These cylinders were regularly tested at 1 day, 3 days, 7 days and 28 days to check the gain in strength of concrete. Concrete cylinders were tested at the laboratory at The University of Texas at Austin. The specified strength of normal strength beams was 7000 psi and that for the high strength beams was 13000 psi. However, 28 day strength of the normal strength concrete was nearly 7000 psi and that of the high strength concrete was 13500 psi. Tests for modulus of elasticity were also conducted at the same time to check the modulus of elasticity of concrete. Both concrete compressive strength and modulus of elasticity tests were done according to ASTM testing procedures. The concrete mix designs used are shown in Table 3.1.

Table 3.1 Concrete Mix Design

Material	Batch wt. for NSC beams (wt. lb/yd^3 of concrete)	Batch wt. for HSC beams (wt. lb/yd^3 of concrete)
Cement	452	671
Fly Ash	122	316
Water	202	247
Coarse Aggregate	1885	1918
Fine Aggregate	1264	1029

Normal strength concrete slabs were cast in the Phil M. Ferguson Laboratory of The University of Texas at Austin where testing took place. Concrete cylinders were cured and tested to obtain their compressive strength. The specified strength for the concrete slab was 6000 psi. The slabs of normal strength beams attained a strength of about 7000 psi and those of high strength beams reached 5700 psi at 28 days. In general, targeted strengths of both beams and slabs were achieved successfully (See Table 3.2).

Table 3.2 Actual Concrete Strength

Age of Concrete	HPC Composite Section Strength (psi)	NSC Composite Section Strength (psi)
Concrete Beam		
At Testing of Section	13337	7201
Composite Deck		
At testing of Section	5507	6815

3.3.2 Steel Properties

Grade 60 steel was used for the reinforcement of the slab and as shear reinforcement in the beam. The prestressing strands used in the beams were grade 270 low relaxation with 0.6 inch diameter. Tensile tests were conducted at the Construction Materials Research Group Laboratory to check ultimate strength of the steel. Stress-strain curves for these tests are presented in Appendix-B.

3.4 Casting of Beams

The beams were fabricated at the Texas Concrete Company prestressing plant in Victoria, Texas. These beams were fabricated on 10^{th} July, 1995.

3.4.1 Concreting Procedure

All beams were cast in a single line. Strands were stressed to about 74% of their ultimate strength of 270 ksi and reinforcement was placed in position by 2:00 P.M. The steel forms were then placed in position. Forms were properly oiled before pouring of concrete. Proper care was taken to avoid getting oil on the surface of strands. Concrete was supplied from the batch plant at the prestressing plant. Concrete was placed and vibrated properly to achieve good consolidation. Concrete cylinders were prepared to test the concrete strength at both the prestressing plant and at the laboratory.

Concrete beams were covered with burlap and cured adequately to achieve targeted concrete strengths required before releasing the prestress in less than 24 hours. Instrumentation was done to monitor heat of hydration of concrete.

3.4.2 Removal of Formwork and Instrumentation

The next morning around 8:00 A.M., formwork was removed after testing concrete cylinders which showed that the required concrete strength had been achieved. Instrumentation was installed after removal of forms. Instrumentation was used to measure transfer length and end slip of strands at the time of transfer.

DEMEC gauges were used to measure concrete strain at transfer. DEMEC points are stainless steel disks about 1/8 in. thick and about ¼ in. in diameter. Each disc has a hole in the center to support the end of the DEMEC gauge when taking measurements. DEMEC points were placed 200 mm apart at the level of the lower strand row, and epoxy was used to place the DEMEC points. DEMEC points were placed on both ends and on both sides of the beam. DEMEC gauges were placed up to 8.5 ft from the end of the beam with gauge points at 50 mm on center. Initial micro strain readings were taken after installation of all DEMEC points. Readings were taken using the DEMEC gauge, and each readings was taken twice to confirm the previous reading.

Instrumentation was also installed on the end of beam strands using a micrometer to measure end slip after transfer of prestress. Initial readings were taken by electronic gauges. It took about 7 hours to finish all instrumentation and measurement of readings.

3.4.3 Transfer of Prestress

Concrete cylinders were tested before transfering the prestress to ensure sufficient concrete strength for the beam at transfer. Transfer of prestress occurred by gradual release of the hydraulic rams about 24 hours after casting of the concrete beams. Prestressing strands were cut by oxyacetylene flame after the force was released. Strands were cut at both ends and between two beams at a point about 18 inches from the end of the beam. After transfer of prestress, appreciable camber was observed.

3.4.4 Measurement of Final Readings

Final readings of both transfer length and end slip were obtained after the transfer of prestress. Carefully planned procedures were used to measure concrete strain and end slip. DEMEC gauges were used to measure concrete micro strain readings after transfer of prestress. Final readings of the strand slip were taken with a micrometer. Strand slip was determined from the difference between final and initial readings.

3.5 Casting of slabs

The beams cast at the prestressing plant were transported to the laboratory by truck. The beams were placed on three concrete pedestals (see Figure 3.2) and wooden formwork for the slabs was installed at the FSEL. Forms were adjusted and placed at the same level as the top of the beams. A surveying instrument was used to level slab forms so that a perfectly level composite slab could be achieved. Forms were properly oiled before placing reinforcement for the slab. All the gaps in the forms were filled by using silicon to avoid leakage of concrete during casting of the slab. The setup of formwork for the slab is shown in Figure 3.2.

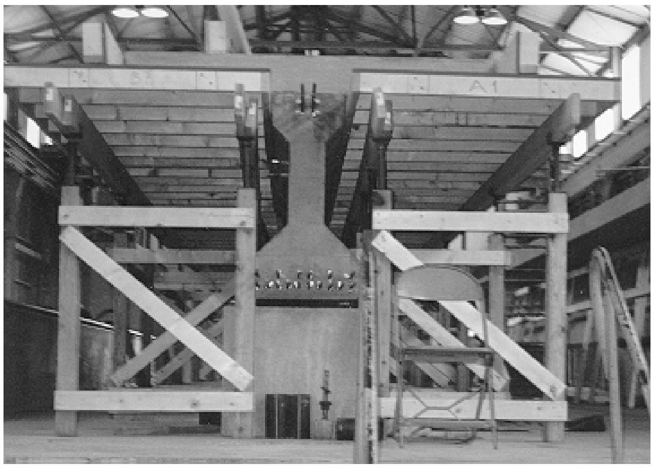

Figure 3.2 Formwork setup for slab

Adequate measures were taken to get good quality concrete for the composite slab. Concrete cylinders were made at the time of concreting. Concrete was properly vibrated to avoid honeycombing. The poured concrete slab was covered by plastic and the slab was properly cured. Slab forms were removed after checking 3-day strength gained by the slab. Concrete cylinders were also tested at 14 and 28 days.

3.6 Experiment requirements

Before testing of the completed beams could begin, two primary goals were necessary to achieve; first was to plan and execute the fabrication of a testing frame, and second was to set up the data acquisition system.

3.6.1 Fabrication of Testing Frame

The testing frame was fabricated at the Ferguson laboratory. A steel test frame used in a previous research project was modified in the laboratory to meet requirements for testing of the composite beams. A one million pound ram was used to apply loads. A spreader beam was used to get two load points providing a constant moment region. The loading pattern was to apply two point loads at 4 ft. spacing (See Figure 3.6). Special rollers were used to move the loading ram to achieve constant moment requirements at each particular embedment length. To achieve easy movement of the whole testing frame a 4 inch hole was made in the diaphragm of the frame, and a pin of about 3.5 inch diameter was inserted in it. The whole frame was then very easy to lift by the 25 ton capacity overhead crane available in the laboratory. Easy movement of the loading ram by use of rollers and movement of the whole frame with crane saved substantial time for completing each test setup.

The frame (see Figure 3.3) was placed at the position required to achieve a selected embedment length. Two bolts in each column base plate (a total of eight bolts) were post tensioned to 100 kips each. In the first couple of tests a plumb bob was suspended from the top of the frame to monitor sidesway of the frame during testing of the concrete beam. The loading frame used is shown in the photograph of Figure 3.3.

Figure 3.3 Movement of test frame by over head crane

3.6.2 Instrumentation of Beam and Slab

To complete the test setup, the beam and slab were properly instrumented. Instrumentation was required to monitor the amount of load applied, concrete strain at the top of slab, to measure end slip of strands, and deflection of the beam. Electronic gauges were used to record readings in terms of voltage differences and then all voltage readings were converted to engineering units by use of the HPDAS2 program. At every load stage all channels were scanned and readings were printed.

Different channels were used to record pressure in the ram, load applied, deflections at supports and load points, concrete strain at top of slab and end slip of strands.

3.6.3 Placement of Gauges

Loading during the test was applied by using a hydraulic pump powered by compressed air. An electronic pressure gauge was attached to the pump to measure the pressure applied to the loading ram, and a mechanical pressure gauge was also attached to check the loading rate. A load cell was used to measure the load directly. A cross check was done in the beginning of each test by multiplying pressure gauge reading and area of ram to compare it with the load reported by the load cell.

Linear potentiometers or linear pots were used at the bottom of the beam to measure deflection of the beam. Linear pots were installed at loading points and midway between loading points. Dial gauges were also used as a backup system. Glass microscopic slides were glued on the beam surface to provide a smooth surface for the tip of the linear pots.

To measure end slip of strands during the tests, linear pots were used. Because the end of the beam cross section was not smooth, plexi glass was glued on the end of the beam. Linear pots were then securely tightened to the individual strands to avoid slippage of the pot itself. All strands were instrumented in the same way to measure end slip of the strand during the test. Instrumentation to measure end slip is shown in the photograph of Figure 3.4.

Electronic strain gauges were installed at the top of the slab to measure concrete strain during the test. The main reason for these gauges was to monitor the concrete strain and to avoid explosive compressive failures. Mechanical strain gauges were also installed and readings were taken at every load stage as a backup system. Figure 3.5 shows strain gauges installed on top of the slab, and also the two point loading system. An electronic plotter was used to plot the load deflection response during the test.

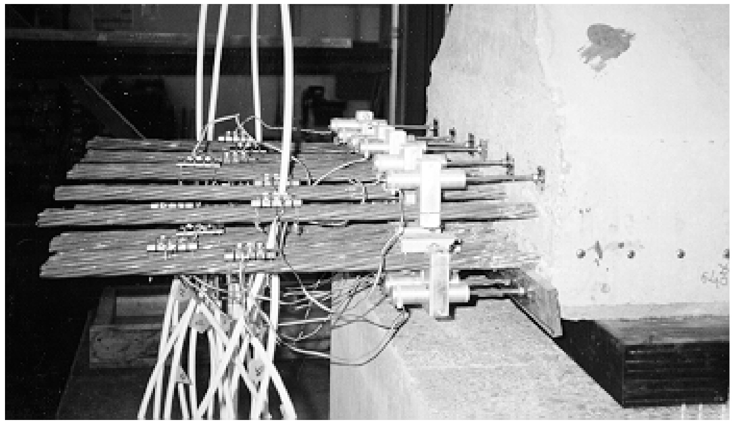

Figure 3.4 Instrumentation for measurement of end slip

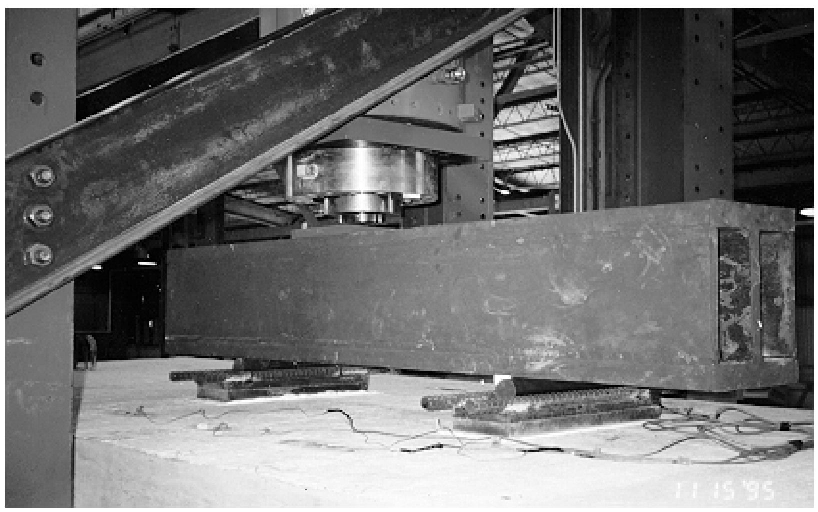

Figure 3.5 Two point loading system

3.6.4 Testing Procedure

Once all instrumentation was completed, the beam was ready to test (see Figure 3.6). The beam was cantilevered at one end so that part of the beam remain uncracked and could later be used for another development length test. When the beam was cantilevered, cracks in the slab occurred in the cantilevered portion of slab. The beam surface was cleaned properly before the test to provide a smooth surface to mark flexural and shear cracks. Before each test, temperature and shrinkage cracks were marked. All linear pots were set to initial zero before the test. All linear pots were tested again to check their accuracy. The test setup is shown in Figure 3.6.

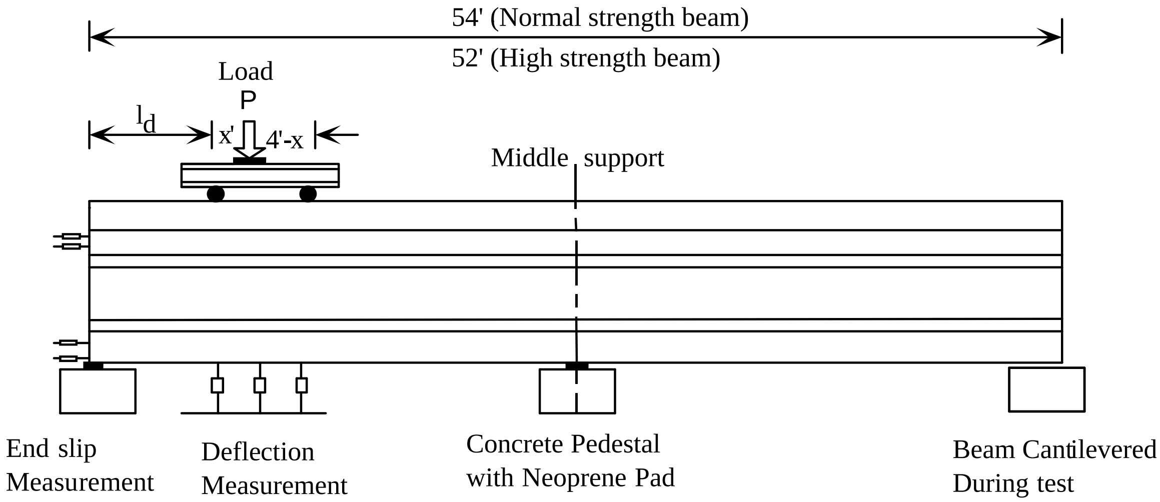

Figure 3.6 Test setup

Loading was started after all initial checks of instrumentation. Load was applied in increments of 40 kips. This 40 kip load increment was estimated from the load deflection curve. After each loading application, all channels were scanned and readings were printed. All scanned readings were saved on hard disk automatically. After this, readings from all mechanical dial gauges and DEMEC strain gauges were taken and recorded. Load increments were applied in the same manner until the first flexural or shear crack was reported. Different colored pens were used to mark flexural and shear cracks. Cracks were also marked underneath the beam. Propagation of existing cracks was marked with the load value after each loading increment. Additional scans were also taken whenever appreciable sound of strand slippage was heard. Load increments of 20 kips were used after the first crack. A displacement increment was adopted when the highly inelastic stage was reached. Loading was applied to produce 0.1 inch deflection. Loading was stopped at a concrete compressive strain of nearly 0.0025 to avoid an explosive compression failure. Steel strain and deflection of the beam were monitored after each load stage. Crack widths were also measured at certain selected points at the different loading stages.

Loading was stopped when concrete strain reached around 0.0025 and steel strain reached more than 3.5%. Channels were scanned two or three times while unloading.

Depending upon the failure mode for the beam, i.e. whether bond failure or flexural failure, embedment length for the next test was decided.

CHAPTER FOUR

TEST RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents end slip test data for both the high strength and the normal strength composite beams. The end slip measurements at the time of transfer and after the development length tests will be presented. The end slip results obtained will be discussed and will be compared in this chapter with some previous research.

4.2 Test Results

Two high performance concrete (HPC) beams were tested first. The development length tests were performed with four different embedment lengths. The experiment was conducted as described in the previous chapter. A summary of the test results for the HPC is given in Table 4.1.

Table 4.1 Summary of Test Results of the High Strength Concrete Beams

	HPC-1-S	HPC-1-N	HPC-2-N	HPC-2-S
Span length (ft.)	25.83	25.83	25.83	25.67
l_d (ft.)	10	7.75	6.5	6
1st Shear crack load (kips)	483	483	461	470
1st Flexural crack load (kips)	470	545	590	622
Maximum Load (kips)	682	766	827	880
Concrete strain at top of slab	0.00266	0.00252	0.00267	0.00247
Strain in steel	3.1%	3.4%	3.2%	3.3%
Maximum crack width (in.)	0.13	0.15	0.10	0.13
Failure type	Flexural	Flexural	Flexural	Flexural

Two normal strength concrete (NSC) beams were tested with the same four embedment lengths as used for the HPC beams. The results obtained during these tests are summarized in Table 4.2.

Table 4.2 Summary of Test Results of the Normal Strength Concrete Beams

	NSC-1-S	NSC-1-N	NSC-2-S	NSC-2-N
Span length (ft.)	26.83	26.83	26.83	26.83
l_d (ft.)	10	7.75	6.5	6
1st Shear crack load (kips)	460	545	458	440
1st Flexural crack load (kips)	460	545	558	560

Maximum Load (kips)	674	753	841	871
Concrete strain at top of slab	0.00292	0.00263	0.00273	0.00272
Strain in steel	3.7%	3.5%	3.7%	3.6%
Maximum crack width (in.)	0.13	0.15	0.15	0.11
Failure type	Flexure	Flexure	Flexure	Comp. Strut (Flexure)

The plotter was connected to the data acquisition instrumentation to plot load-deflection response during each of the tests. The end slip of each strand was measured during each load step. The end slip measurements for each strand at transfer and after the development length testing are given in Appendix- C.

4.2.1 End Slip Results

The end slip of each strand was measured at transfer of prestress at the prestressing plant in Victoria, TX. The end slip during the development length tests was measured in the Phil M. Ferguson Laboratory at The University of Texas at Austin. The summary of the maximum and the average end slip at transfer and after the development length tests are given in Table 4.3 and Table 4.4.

Table 4.3 Summary of end slip measurements of High Strength Concrete beams

	HPC-1-S	**HPC-1-N**	**HPC-2-N**	**HPC-2-S**
End slip at transfer (inches)				
Average slip of rows A & B	0.051	0.055	0.037	0.047
Average slip of rows C & D	0.070	0.084	0.067	0.064
Average slip of all strands	0.055	0.061	0.043	0.050
Maximum slip Strand label	0.083 D1	0.104 A4	0.080 D2	0.092 A5
End slip at final load (inches)				

Embedment length (ft.)	10	7.75	6.5	6
Average slip of all strands	0.001	0.012	0.010	0.013
Maximum slip Strand label	0.011 B5	0.048 B5	0.038 B5	0.048 B6

Table 4.4 Summary of end slip measurements of Normal Strength Concrete beams

	NSC-1-S	**NSC-1-N**	**NSC-2-S**	**NSC-2-N**
End slip at transfer (inches)				
Average slip of rows A & B	0.068	0.062	0.074	0.074
Average slip of rows C & D	0.083	0.096	0.078	0.104
Average slip of all strands	0.068	0.069	0.079	0.080
Maximum slip Strand label	0.091 C2	0.100 D1	0.094 A5	0.264 C1
End slip at final load (inches)				
Embedment length (ft.)	10	7.75	6.5	6
Average slip of all strands	0.0	0.004	0.014	0.018
Maximum slip Strand label	0.006 B1	0.021 B5	0.048 B10	0.055 B5

The end slip measurement for each strand of test HPC-1-N are shown graphically in Figure 4.1 and Figure 4.2. The end slip measurements after the transfer of prestress are shown in Figure 4.1 and those after the end of the development length test are presented in Figure 4.2. The other plots of measurements of end slip for the normal strength beams and the high strength beams are given in Appendix-D.

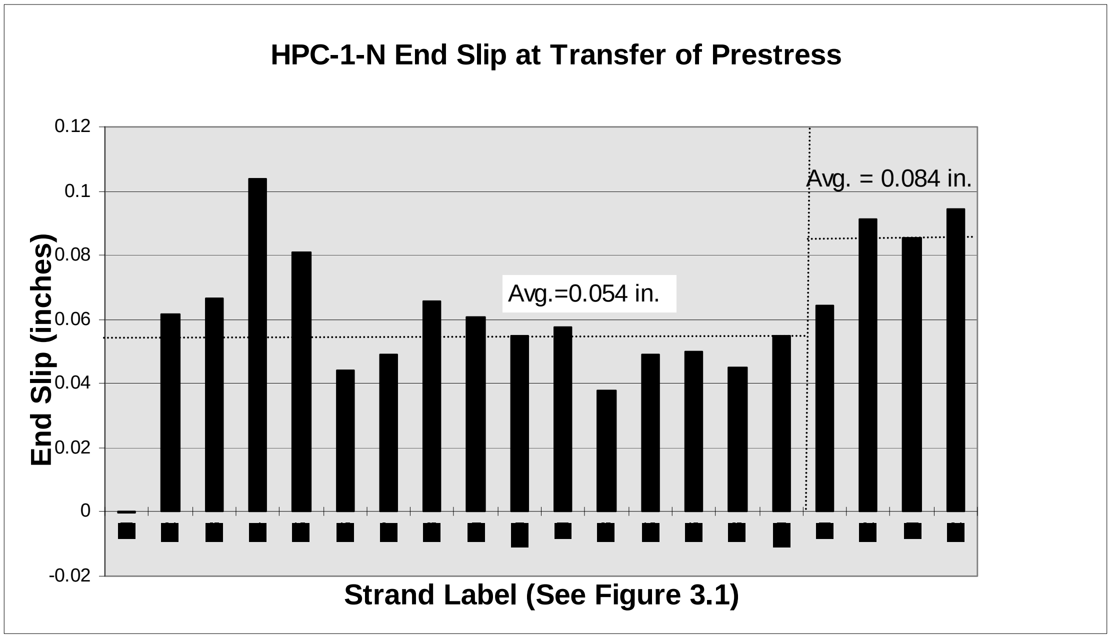

Figure 4.1 End Slip of the Strands After Transfer of Prestress (HPC-1-N)

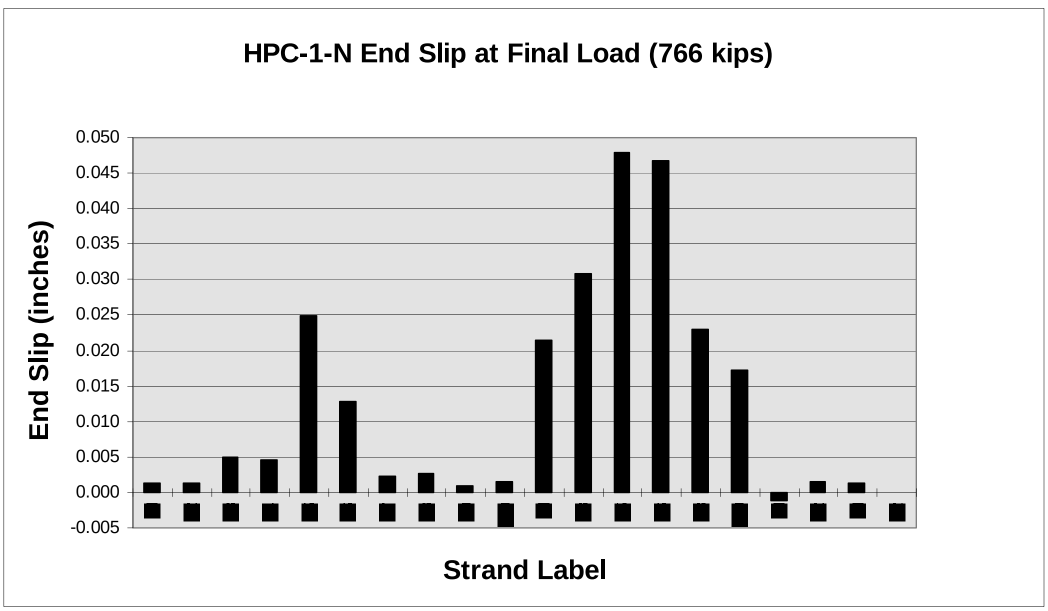

Figure 4.2 End Slip of the Strands After Development Length Test (HPC-1-N)

Figure 4.2 shows negative end slip of strand C1 (one of the four top strands) after the development length test. The negative slip of strands may be the result of slippage of the clamp of the potentiometer or slippage of the potentiometer outwards. However, these negative end slip values are quite small and can be considered as test instrumentation error.

4.3 Test Discussion

Tests for both high strength beams and normal strength beams were performed with the same embedment length. The development length tests were performed with the embedment lengths of 10, 7.75, 6.5 and 6 ft with the two point loading system shown in Figure 3.6.

4.3.1 High Strength Concrete Beams

The high strength test beams failed in flexure for all embedment lengths. At the final loads, the flexural cracks were observed to extend up to 3 inches from the top of the slab (Figure 4.3), the extension of the cracking gave an indication of the position of the neutral axis during the tests for later use in calculating steel strain at the level of strands. The flexural cracks were observed at uniform spacings of about 3-4 inches. The uniform and close crack spacing showed good bond behavior of 0.6 in. diameter strands. The maximum crack width of approximately 1/8” was observed (See Table 4.1 & 4.2) during most of the tests. In each test, minor end slip of the strands was observed as shown in the plots of appendix D, D-9 through D-16. The flexural crack pattern obtained at the end of HPC-1-S test as shown in Figure 4.3 is typical for the constant moment region between load points in all of the beams.

Figure 4.3 Crack Pattern of HPC-1-S During Development Length Test

4.3.2 Normal Strength Concrete Beams

The normal strength beam failed in flexure when tested at the embedment lengths of 10, 7.75 and 6.5 ft. While being tested with embedment length of 6 ft., Beam NSC-2-N failed with an explosive compression-strut failure in the web (Figure 4.4). The test load was at a level which correspond to flexural strength computed for the beam and a deflection of almost 2 inches had developed before failure of beam end NSC-2-N. Extensive web diagonal cracking developed throughout the shear span but, crack widths were quite small prior to crushing failure in the web. The side cover of beam was lost throughout the 6 ft. shear span when crushing occurred. The bent shear reinforcement due to the shearing movements along the critical diagonal crack is shown in the photograph of Figure 4.4. The web shear cracks propagated to the bottom of the beam. Several web shear cracks branched into cracks parallel to the longitudinal strands at the level of strands at the end of the beam. These horizontal cracks at the level of steel strands could have reduced the bond strength and could be responsible for slippage of the strands. At the time of the explosive failure, the large vertical crack (Figure 4.5) was observed at the end of the beam in the lower flange region.

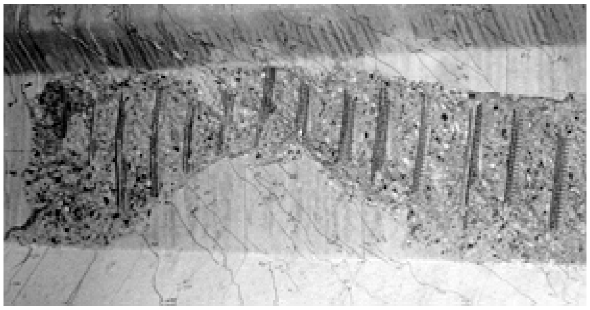

Figure 4.4 Explosive Shear-Compression Failure (Beam NSC-2-N)

Figure 4.5 Cracked Beam End Because of Shear-Compression Failure

It is to be noted that all beams failed in flexure. The normal strength beam tested at an embedment length of 6 ft. showed a compression strut failure after ultimate moment had been developed. It should be noted that the companion test in the HPC series with 6 ft. embedment length had approximately twice the concrete compressive strength as NSC-2-N and the web crushing failure did not occur.

4.3.3 End Slip Results

The graphical presentation of the end slip results of the strands of the beam end HPC-1-N after transfer is shown in Figure 4.1 and plots of the remaining beam ends are given in Appendix D (See Figures D-1 through D-8). The average strand slip of all the strands at transfer for the four HPC beam ends was 0.052 inches (See Table 4.3). The average strand slip of the rows A & B (bottom flange strands) was about 0.048 inches and that of the rows C & D (top flange strands) was about 0.071 inches for all four HPC beam ends at the time of transfer of prestress. The higher average strand slips were observed in the normal strength concrete beams. The average strand slip of four NSC beam ends was 0.074 inches (See Table 4.4). The average slip of rows A & B of 0.070 inches and those of row C & D of 0.090 inches were observed.

It was observed that the strands of the top beam flange showed higher average strand slip values than those of the lower flange strands in both HPC and NSC beams

(Tables 4.3 & 4.4). The higher average strand slip of the top flange strands may be because of the poor bond associated with top strands in structural concrete. Also, the NSC beams showed higher average strand slip (0.074 inches) than the HPC beams (0.052 inches). This could be due to the higher bond strength of the high strength concrete.

The end slip of the strands at the end of the development length tests is given in the lower portions of Tables 4.3 and 4.4. It was observed that (Figure 4.2) the strands of the second row from bottom (row B) of the beam (4 inches from bottom) slipped more than the strands of the first row (row A) strands (2 inches from bottom). It was also noted that strands in the web portion of the beam slipped more than the strands in the bottom flange portion of the beams as shown in Figure 4.2.

The greater slippage of the second row from the bottom (Row B) can be justified as follows. During the tests, when web shear cracks occurred, they propagated towards the bottom of the beam at increasing load, and intersected the top row of strands (Row B) in the bottom flange. These web shear cracks must have weakened the anchorage of some of these strands and thus resulted in higher slippage of strands. Thus, higher web shear stress and the diagonal cracking may be responsible for higher slippage of strands in row B and in the web portion of the beam. Another reason for higher slippage of row B of strands may be because of lower lateral pressure or confinement resulting from the reaction at the support compared to the row A strands (Figure 4.6). It should be noted that the bond strength increases when lateral pressure is applied close to strands[9]. The pressure resulting from the reaction at the end of the beam has more confining effect on the lower row (row A) of strands than the upper row of strands (row B) in the bottom flange. Thus, the bond strength of the lower strands will be higher than for the upper row of strands in the bottom flange. The lower bond strength of the row B strands and the higher web shear stress resulted in higher end slip for the row B strands.

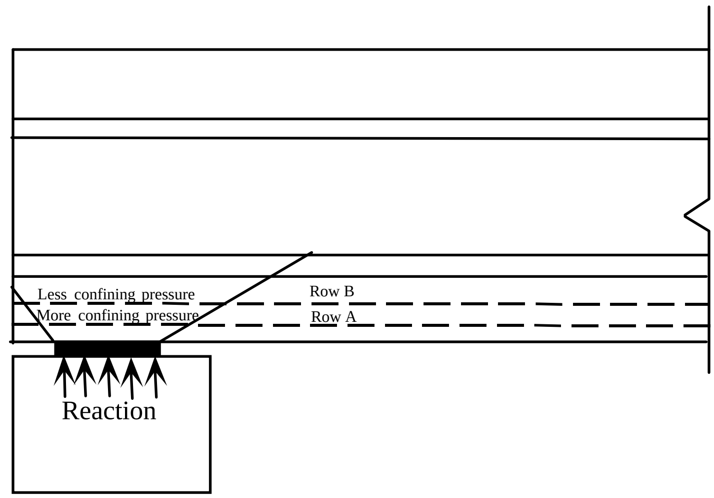

Figure 4.6 Confining pressure effect on the strands

4.4 End Slip Measurements of Previous Research

There are not many test data available for end slip measurement using 0.6 in. diameter strands. Gross [4] reported very good bond behavior of 0.6 in. diameter strands when used in rectangular beams. The maximum end slips that occurred in the development length tests were about 0.002 inches. It should be noted that the rectangular beams had no diagonal cracking due to shear. The surface condition of the strand was rusty, which enhanced the bond for these series.

Russell and Burns [12] also investigated the bond behavior of prestressed concrete beams using 0.5 in. diameter strands and 0.6 in. diameter strands. The test results of Russell and Burns showed better bond behavior with the use of 0.6 in. diameter strands than that with the 0.5 in. diameter strands due to some longitudinal cracking and possible strand contamination in the 0.5 in. diameter test series. The tests also showed small end slip values of about 0.0025 inches during the development length tests.

4.5 Accuracy of End Slip Results

The end slip readings of all the strands were taken electronically during the development length tests to achieve higher accuracy in the measurements. The end slip measurements were taken with an accuracy of one thousandth of an inch for each individual strand. Slip of the strands was recorded at the time of transfer using the initial readings before transfer and the final readings after the transfer of prestressing force. The end slip was calculated from the difference of the initial and final readings taken with a micrometer. In the end slip readings, it has been assumed that the clamps did not move while releasing the prestressing force, and both the initial and the final readings were taken from the same spot of the beam end.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

5.1 Summary

The primary objective of the research study was to investigate transfer length, development length and bond behavior of full scale Texas Type C (I-shape) composite beams which utilize 0.6 inch diameter strands at 2 inch grid spacing. The research program was conducted at the Phil M. Ferguson Structural Engineering Laboratory (FSEL) at The University of Texas at Austin. Two normal strength concrete (NSC) and two high performance concrete (HPC) beams were tested at the FSEL. The specified concrete strengths were 7000 psi for the normal strength beams and 13000 psi for the high strength beams.

The prestressed concrete beams were cast at the Texas Concrete Company at Victoria, TX. The transfer length measurements and the end slip of the strands after transfer of prestress were taken at the prestressed concrete plant. The beams were shipped to FSEL for development length tests. The composite deck slabs of 7.5 inches thick and 72 inches wide were cast at the laboratory.

The high performance concrete beams showed average strand slip of 0.052 inches and the normal strength concrete beams showed average strand slip of 0.074 inches after the transfer of prestressing force. Thus, both the high strength and the normal strength beams showed very good bond behavior of 0.6 inch diameter strands.

The development length tests were performed on the composite beams with four different embedment lengths. The ends of the beams were tested with different embedment lengths. Each end of the normal strength concrete beams and the high strength concrete beams was tested with embedment lengths made progressively shorter as follows; 10, 7.75, 6.5, and 6 ft. The instrumentation was added to allow for the measurement of end slip of each individual strand during the development length tests. All of the high strength concrete beam ends and three of the four normal strength concrete beam ends failed in flexure and showed no general end slip of the strands prior to the final loading. Only the normal strength beam tested at the embedment length of 6 ft. (Beam NSC-2-N) showed the compression strut, web crushing failure after having reached calculated flexural strength. The diagonal compression strut action was responsible for the explosive failure within the web throughout the shear span after flexural ultimate failure load had been reached.

5.2 Conclusions

The following conclusions were drawn from this research study:

1. The use of 0.6 inch diameter strands showed very good bond behavior in fully bonded Texas Type C (I-shaped) composite girders with no cracking at transfer with strand spacing 2 in. on center.
2. The normal strength concrete beam strands showed average end slip of about 0.074 inches which was higher than that of the high strength concrete beam (0.052 inches) after transfer of prestress.
3. The strands in row B (4 in. from bottom) of the bottom flange slipped more than those of row A (2 in. from bottom). The lower amount of lateral pressure or confinement provided by the reaction at the end of the beam is primarily responsible for the slightly higher strand slip of the strands in row B of the bottom flange for both HPC and NSC beams.
4. In the development length tests of both HPC and NSC beams of this series, no general slip of strands occurred even with an embedment length of 6 ft. Thus, the development length is less than 72 inches for 0.6 in. diameter strand based on these tests.
5. The strands in the top flange of the normal strength concrete beam showed average strand slip of 0.090 inches which was higher than the average strand slip in the bottom flange (0.070 inches). Similar behavior was observed in the high strength concrete beams in which the strands in the top flange slipped 0.071 inches and the strands in the bottom flange showed average slip of 0.048 inches. The strands in the top flange showed higher end slip due to "top bar" effect as noted for structural concrete members.

APPENDIX A

DRAWING OF THE TEST SPECIMENS

APPENDIX B

TENSILE TEST RESULTS OF 0.6 IN. DIAMETER LOW RELAXATION STRANDS

APPENDIX C

END SLIP MEASUREMENTS AT TANSFER
AND
AFTER DEVELOPMENT LENGTH TESTS

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	89.18	0.00	0.00	0.64	0.00	0.00
A2	90.62	88.40	2.22	0.66	1.56	0.062
A3	85.89	83.58	2.31	0.62	1.69	0.066
A4	84.74	81.49	3.25	0.61	2.64	0.104
A5	83.23	80.57	2.66	0.60	2.06	0.081
A6	93.71	91.90	1.80	0.68	1.13	0.044
A7	92.79	90.87	1.91	0.67	1.24	0.049
A8	93.24	90.90	2.34	0.67	1.67	0.066
A9	96.25	94.01	2.24	0.70	1.54	0.061
A10	103.58	101.44	2.14	0.75	1.39	0.055
B1	51.46	49.62	1.84	0.37	1.46	0.058
B3	53.36	52.01	1.35	0.39	0.96	0.038
B5	52.04	50.41	1.63	0.38	1.25	0.049
B6	54.91	53.24	1.67	0.40	1.27	0.050
B8	50.19	48.68	1.51	0.36	1.15	0.045
B10	52.20	50.43	1.77	0.38	1.39	0.055
C1	53.96	51.94	2.02	0.39	1.63	0.064
C2	49.91	47.23	2.68	0.36	2.31	0.091
D1	53.09	50.53	2.56	0.38	2.18	0.086
D2	54.83	52.03	2.80	0.40	2.40	0.094

Table C-1 End Slip Measurements at Transfer (Beam End HPC-1-N)

Actual end slip = (Measured End Slip) - (Elastic shortening)

Elastic Shortening = (f_{si} . Initial Reading) / E_{ps}

<u>Sample Calculation for Reading A1</u>

Elastic Shortening = (202.5) (89.18)/28000
=0.64 mm

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	68.34	66.46	1.88	0.49	1.39	0.055
A2	68.42	66.57	1.85	0.49	1.36	0.053
A3	67.89	65.72	2.18	0.49	1.68	0.066
A4	66.68	64.54	2.14	0.48	1.66	0.065
A5	62.89	60.86	2.04	0.45	1.58	0.062
A6	68.19	65.99	2.21	0.49	1.71	0.067
A7	62.04	60.04	2.00	0.45	1.55	0.061
A8	63.32	61.32	2.00	0.46	1.54	0.061
A9	67.82	65.84	1.99	0.49	1.49	0.059
A10	68.80	67.07	1.73	0.50	1.23	0.049
B1	51.91	48.18	3.74	0.38	0.00	0.000
B3	52.07	50.81	1.26	0.38	0.88	0.035
B5	52.01	50.45	1.56	0.38	1.18	0.047
B6	51.57	49.98	1.59	0.37	1.22	0.048
B8	50.22	48.89	1.34	0.36	0.97	0.038
B10	52.01	50.40	1.61	0.38	1.23	0.048
C1	52.93	51.04	1.89	0.38	1.50	0.059
C2	51.45	49.30	2.15	0.37	1.78	0.070
D1	50.93	48.46	2.47	0.37	2.10	0.083
D2	52.19	50.05	2.14	0.38	1.76	0.069

Table C-2 End Slip Measurements at Transfer (Beam End HPC-1-S)

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	83.77	81.29	2.48	0.61	1.87	0.074
A2	81.07	0.00	0.00	0.59	0.00	0.000
A3	86.46	84.73	1.74	0.63	1.11	0.044
A4	85.10	83.31	1.79	0.62	1.18	0.046
A5	115.59	113.69	1.90	0.84	1.06	0.042
A6	121.05	119.09	1.96	0.88	1.08	0.043
A7	79.76	78.21	1.55	0.58	0.97	0.038
A8	79.18	0.00	0.00	0.57	0.00	0.000
A9	88.34	86.54	1.79	0.64	1.16	0.046
A10	90.42	88.83	1.59	0.65	0.93	0.037
B1	51.38	49.94	1.45	0.37	1.07	0.042
B3	55.07	53.70	1.37	0.40	0.97	0.038
B5	52.39	51.10	1.29	0.38	0.91	0.036
B6	51.37	50.03	1.35	0.37	0.97	0.038
B8	51.50	50.28	1.22	0.37	0.85	0.033
B10	51.73	50.31	1.43	0.37	1.05	0.041
C1	52.83	50.75	2.09	0.38	1.70	0.067
C2	50.68	48.73	1.95	0.37	1.58	0.062
D1	50.23	48.42	1.81	0.36	1.44	0.057
D2	51.48	49.08	2.40	0.37	2.03	0.080

Table C-3 End Slip Measurements at Transfer (Beam End HPC-2-N)

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	82.60	81.02	1.58	0.60	0.98	0.039
A2	73.71	71.98	1.74	0.53	1.20	0.047
A3	73.58	71.62	1.96	0.53	1.43	0.056
A4	73.60	71.79	1.81	0.53	1.28	0.050
A5	74.95	72.07	2.88	0.54	2.34	0.092
A6	73.94	71.87	2.07	0.53	1.54	0.060
A7	72.84	71.18	1.65	0.53	1.13	0.044
A8	70.60	68.81	1.79	0.51	1.28	0.050
A9	71.32	69.61	1.71	0.52	1.19	0.047
A10	69.01	67.38	1.64	0.50	1.14	0.045
B1	50.49	49.15	1.34	0.37	0.97	0.038
B3	49.81	48.69	1.13	0.36	0.76	0.030
B5	51.06	49.71	1.35	0.37	0.98	0.038
B6	51.10	49.90	1.20	0.37	0.83	0.032
B8	51.12	49.90	1.22	0.37	0.85	0.033
B10	50.83	49.32	1.51	0.37	1.14	0.045
C1	50.76	48.49	2.27	0.37	1.90	0.075
C2	53.25	51.62	1.63	0.39	1.24	0.049
D1	50.57	48.39	2.18	0.37	1.81	0.071
D2	50.68	48.81	1.87	0.37	1.50	0.059

Table C-4 End Slip Measurements at Transfer (Beam End HPC-2-S)

	fsu [ksi]=	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	87.49	85.23	2.27	0.63	1.63	0.064
A2	87.74	86.09	1.66	0.63	1.02	0.040
A3	87.86	85.56	2.30	0.64	1.66	0.065
A4	85.75	83.66	2.09	0.62	1.47	0.058
A5	80.29	77.74	2.55	0.58	1.97	0.078
A6	85.95	83.65	2.30	0.62	1.68	0.066
A7	85.10	82.94	2.16	0.62	1.54	0.060
A8	81.19	78.94	2.25	0.59	1.66	0.065
A9	81.71	79.45	2.26	0.59	1.67	0.066
A10	83.75	81.87	1.88	0.61	1.27	0.050
B1	50.19	48.17	2.02	0.36	1.66	0.065
B3	54.72	52.86	1.86	0.40	1.46	0.058
B5	50.17	48.11	2.07	0.36	1.70	0.067
B6	51.12	49.24	1.88	0.37	1.51	0.059
B8	51.19	49.17	2.02	0.37	1.64	0.065
B10	50.87	48.96	1.91	0.37	1.54	0.061
C1	52.34	49.47	2.87	0.38	2.49	0.098
C2	51.20	48.42	2.79	0.37	2.41	0.095
D1	51.36	48.45	2.91	0.37	2.54	0.100
D2	50.48	47.85	2.63	0.37	2.26	0.089

Table C-5 End Slip Measurements at Transfer (Beam End NSC-1-N)

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	72.57	69.90	2.66	0.52	2.14	0.084
A2	70.68	68.20	2.48	0.51	1.97	0.078
A3	72.66	69.99	2.67	0.53	2.14	0.084
A4	77.54	75.06	2.47	0.56	1.91	0.075
A5	82.06	79.99	2.07	0.59	1.48	0.058
A6	68.49	66.66	1.83	0.50	1.33	0.052
A7	50.11	47.92	2.19	0.36	1.83	0.072
A8	59.56	57.07	2.49	0.43	2.06	0.081
A9	67.90	65.84	2.05	0.49	1.56	0.062
A10	69.11	67.05	2.06	0.50	1.56	0.061
B1	52.16	49.72	2.44	0.38	2.06	0.081
B3	53.69	51.69	2.00	0.39	1.61	0.063
B5	49.12	47.48	1.65	0.36	1.29	0.051
B6	53.25	51.57	1.68	0.39	1.29	0.051
B8	51.77	49.71	2.06	0.37	1.68	0.066
B10	54.05	52.08	1.97	0.39	1.58	0.062
C1	53.28	50.91	2.37	0.39	1.98	0.078
C2	51.04	48.38	2.67	0.37	2.30	0.090
D1	50.11	47.54	2.57	0.36	2.21	0.087
D2	53.45	51.10	2.35	0.39	1.96	0.077

Table C-6 End Slip Measurements at Transfer (Beam End NSC-1-S)

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	96.44	93.77	2.67	0.70	1.97	0.077
A2	88.11	85.45	2.66	0.64	2.02	0.079
A3	92.05	89.73	2.33	0.67	1.66	0.065
A4	86.76	84.38	2.38	0.63	1.75	0.069
A5	92.67	90.33	2.35	0.67	1.67	0.066
A6	90.78	88.42	2.36	0.66	1.70	0.067
A7	91.46	88.30	3.16	0.66	2.50	0.098
A8	89.81	87.58	2.24	0.65	1.59	0.062
A9	82.93	80.49	2.45	0.60	1.85	0.073
A10	75.78	73.37	2.42	0.55	1.87	0.074
B1	51.34	48.75	2.59	0.37	2.22	0.087
B3	50.20	48.03	2.18	0.36	1.81	0.071
B5	50.81	48.51	2.30	0.37	1.93	0.076
B6	50.57	48.52	2.06	0.37	1.69	0.067
B8	50.49	48.36	2.13	0.37	1.76	0.069
B10	50.92	48.59	2.33	0.37	1.96	0.077
C1	51.61	48.32	3.29	0.37	2.92	0.115
C2	50.38	47.53	2.86	0.36	2.49	0.098
D1	50.67	47.40	3.28	0.37	2.91	0.115
D2	51.13	48.50	2.63	0.37	2.26	0.089

Table C-7 End Slip Measurements at Transfer (Beam End NSC-2-N)

	fsu [ksi] =	270		Aps [in2] =	0.215	
	fsi [ksi] =	202.5		Eps [ksi] =	28,000	
Strand	Initial	Final	Difference	Elastic	End	End
Label	Reading	Reading		Shortening	Slip	Slip
	(mm)	(mm)	(mm)	(mm)	(mm)	(inches)
A1	77.34	74.72	2.63	0.56	2.07	0.081
A2	76.11	73.28	2.83	0.55	2.28	0.090
A3	76.27	73.37	2.90	0.55	2.34	0.092
A4	70.11	67.63	2.48	0.51	1.97	0.077
A5	74.40	71.47	2.93	0.54	2.39	0.094
A6	70.00	67.69	2.31	0.51	1.80	0.071
A7	73.11	70.50	2.61	0.53	2.09	0.082
A8	70.60	68.12	2.47	0.51	1.96	0.077
A9	74.82	72.49	2.33	0.54	1.79	0.070
A10	75.02	72.60	2.42	0.54	1.88	0.074
B1	50.61	48.31	2.30	0.37	1.93	0.076
B3	49.79	47.56	2.22	0.36	1.86	0.073
B5	49.82	47.29	2.53	0.36	2.16	0.085
B6	51.13	48.91	2.22	0.37	1.85	0.073
B8	50.88	48.65	2.23	0.37	1.86	0.073
B10	51.61	49.30	2.31	0.37	1.94	0.076
C1	50.98	48.38	2.60	0.37	2.23	0.088
C2	50.00	47.77	2.22	0.36	1.86	0.073
D1	52.00	49.48	2.53	0.38	2.15	0.085
D2	52.25	50.22	2.03	0.38	1.65	0.065

Table C-8 End Slip Measurements at Transfer (Beam End NSC-2-S)

	HPC-1-N	
Strand	Slip	Slip
Label	(inch)	(mm)
A1	0.001	0.035
A2	0.001	0.031
A3	0.005	0.128
A4	0.005	0.117
A5	0.025	0.632
A6	0.013	0.325
A7	0.002	0.057
A8	0.003	0.066
A9	0.001	0.025
A10	0.002	0.041
B1	0.021	0.544
B3	0.031	0.784
B5	0.048	1.218
B6	0.047	1.187
B8	0.023	0.582
B10	0.017	0.439
C1	-0.001	-0.030
C2	0.002	0.040
D1	0.001	0.032
D2	0.000	0.001

Table C-9 End Slip Measurement After Development length Test (HPC-1-N)

	HPC-1-S	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	0.000	-0.003
A2	0.000	-0.002
A3	-0.003	-0.065
A4	0.000	-0.002
A5	0.004	0.089
A6	0.000	-0.002
A7	0.000	-0.008
A8	0.000	-0.010
A9	-0.001	-0.029
A10	0.000	-0.006
B1	0.002	0.056
B3	0.004	0.104
B5	0.011	0.278
B6	0.005	0.122
B8	0.003	0.079
B10	0.002	0.055
C1	0.000	0.004
C2	0.000	0.004
D1	0.000	0.004
D2	0.000	0.004

Table C-10 End Slip Measurement After Development length Test (HPC-1-S)

	HPC-2-N	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	0.004	0.090
A2	0.000	0.000
A3	0.005	0.127
A4	0.012	0.312
A5	0.021	0.535
A6	0.005	0.125
A7	0.002	0.039
A8	-0.001	-0.016
A9	0.000	0.007
A10	0.015	0.371
B1	0.025	0.646
B3	0.016	0.395
B5	0.038	0.969
B6	0.008	0.194
B8	0.016	0.396
B10	0.028	0.700
C1	-0.001	-0.025
C2	0.001	0.026
D1	0.009	0.238
D2	-0.001	-0.017

Table C-11 End Slip Measurement After Development length Test (HPC-2-N)

	HPC-2-S	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	0.016	0.412
A2	0.001	0.015
A3	-0.002	-0.058
A4	0.001	0.020
A5	0.002	0.053
A6	0.023	0.589
A7	0.005	0.118
A8	0.000	-0.001
A9	0.000	-0.002
A10	0.011	0.289
B1	0.044	1.108
B3	0.024	0.619
B5	0.022	0.552
B6	0.048	1.215
B8	0.032	0.809
B10	0.035	0.879
C1	0.000	0.003
C2	-0.001	-0.016
D1	0.000	-0.007
D2	0.000	-0.007

Table C-12 End Slip Measurement After Development length Test (HPC-2-S)

	NSC-1-N	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	-0.001	-0.015
A2	0.001	0.031
A3	0.002	0.046
A4	0.000	0.013
A5	0.001	0.022
A6	0.013	0.334
A7	0.001	0.027
A8	-0.001	-0.016
A9	0.000	-0.006
A10	-0.002	-0.038
B1	0.003	0.085
B3	0.002	0.044
B5	0.021	0.541
B6	0.019	0.486
B8	0.004	0.103
B10	0.006	0.149
C1	0.000	0.001
C2	0.002	0.045
D1	0.001	0.035
D2	0.000	0.012

Table C-13 End Slip Measurement After Development length Test (NSC-1-N)

	NSC-1-S	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	-0.001	-0.035
A2	-0.001	-0.015
A3	-0.008	-0.192
A4	0.000	-0.001
A5	-0.003	-0.067
A6	0.000	-0.004
A7	0.000	-0.003
A8	0.000	-0.008
A9	0.000	0.002
A10	-0.002	-0.051
B1	0.006	0.150
B3	0.001	0.030
B5	0.000	0.007
B6	0.001	0.034
B8	0.000	-0.006
B10	0.000	-0.009
C1	0.000	-0.001
C2	0.000	-0.005
D1	0.000	-0.001
D2	0.000	0.000

Table C-14 End Slip Measurement After Development length Test (NSC-1-S)

	NSC-2-N	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	0.029	0.737
A2	0.000	-0.010
A3	0.004	0.094
A4	0.022	0.553
A5	0.032	0.823
A6	0.035	0.896
A7	0.010	0.255
A8	0.003	0.072
A9	-0.001	-0.015
A10	0.017	0.440
B1	0.044	1.126
B3	0.017	0.437
B5	0.055	1.404
B6	0.041	1.032
B8	0.028	0.700
B10	0.032	0.816
C1	0.000	-0.003
C2	-0.015	-0.391
D1	0.003	0.064
D2	0.000	-0.007

Table C-15 End Slip Measurement After Development length Test (NSC-2-N)

	NSC-2-S	
Strand	Slip	Slip
Label	(inches)	(mm)
A1	0.007	0.187
A2	0.001	0.023
A3	0.001	0.032
A4	0.015	0.374
A5	0.027	0.688
A6	0.021	0.530
A7	0.003	0.065
A8	0.004	0.092
A9	0.001	0.034
A10	0.015	0.372
B1	0.019	0.470
B3	0.027	0.680
B5	0.034	0.852
B6	0.027	0.690
B8	0.030	0.749
B10	0.048	1.213
C1	-0.001	-0.027
C2	-0.001	-0.037
D1	0.000	0.006
D2	0.000	0.001

Table C-16 End Slip Measurement After Development length Test (NSC-2-S)

APPENDIX D

GRAPHICAL PRESENTATION OF END SLIP MEASUREMENTS

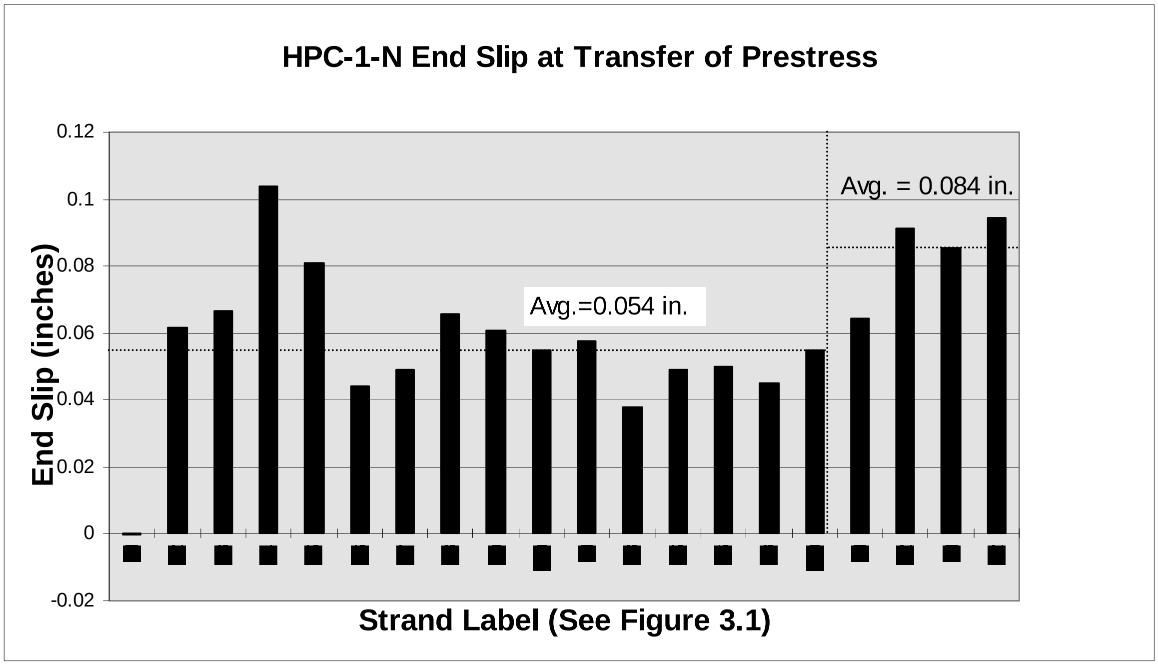

Fig. D-1 End slip of beam end HPC-1-N at transfer

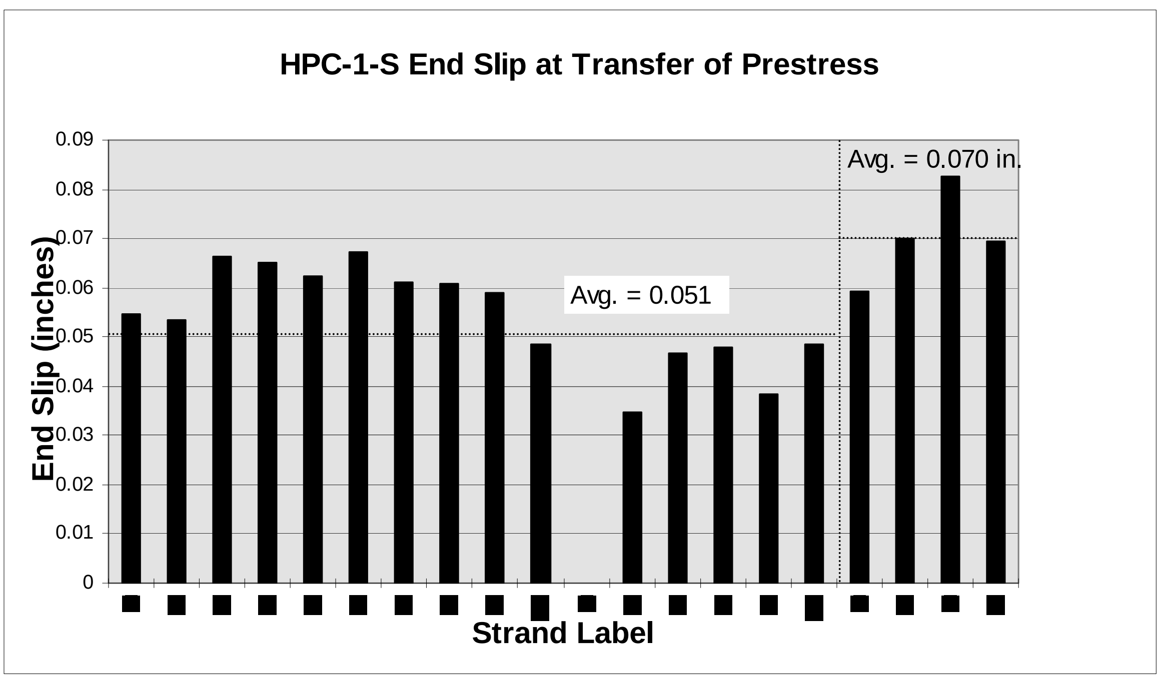

Fig. D-2 End slip of beam end HPC-1-S at transfer

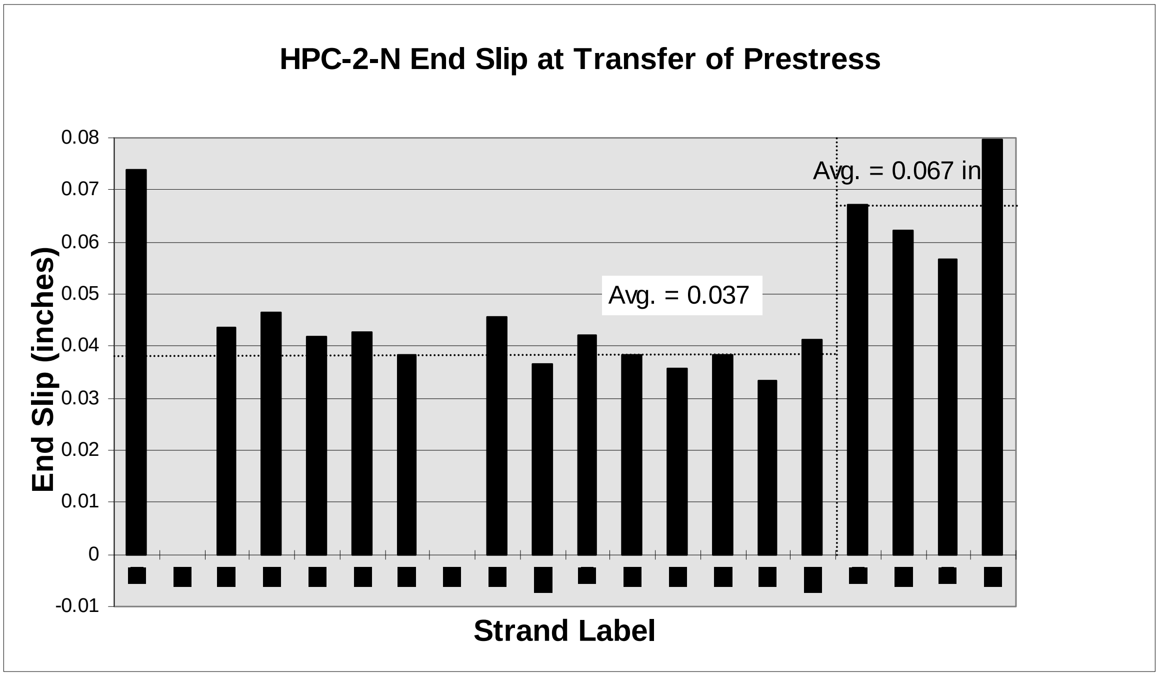

Fig. D-3 End slip of beam end HPC-2-N at transfer

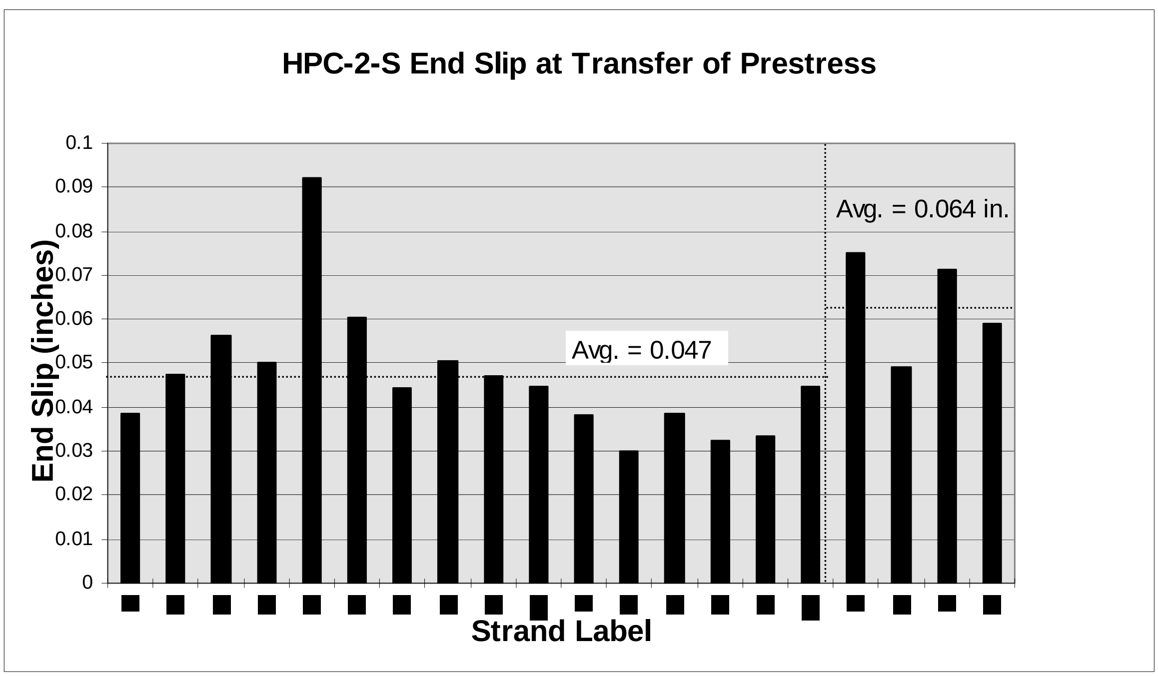

Fig. D-4 End slip of beam end HPC-2-S at transfer

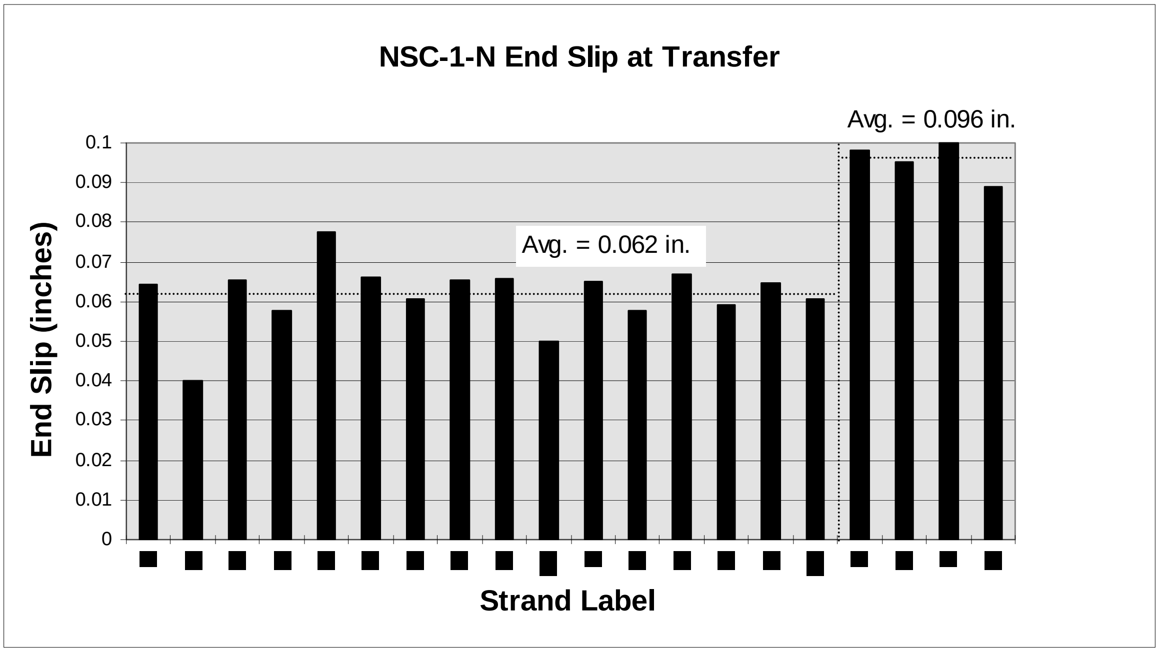

Fig. D-5 End slip of beam end NSC-1-N at transfer

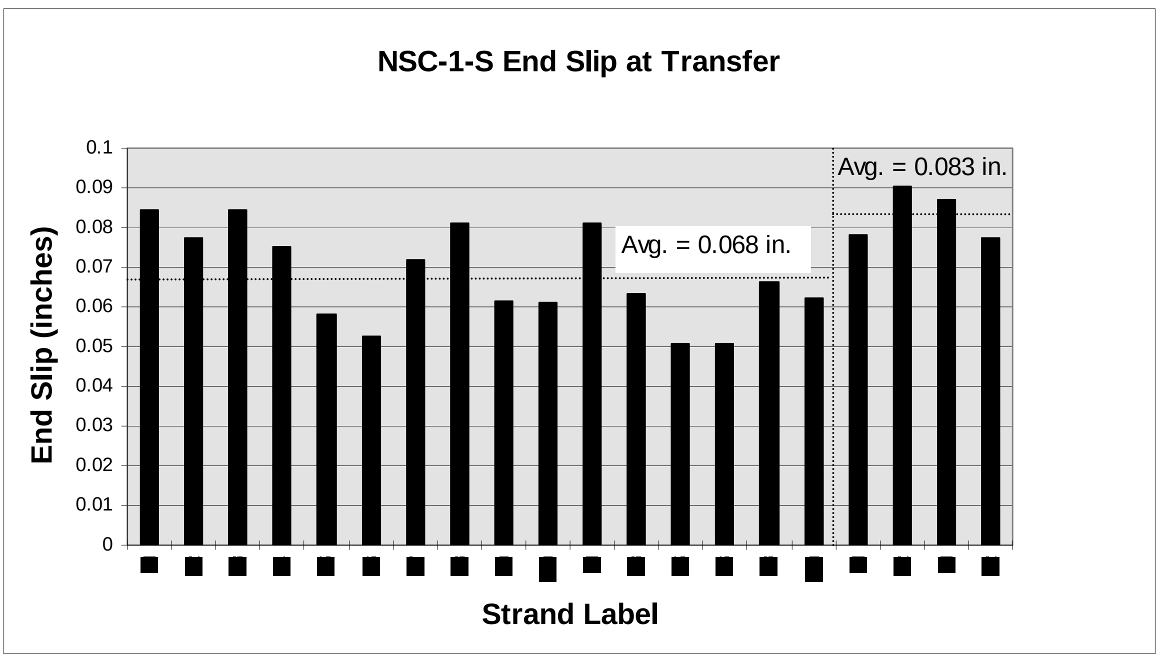

Fig. D-6 End slip of beam end NSC-1-S at transfer

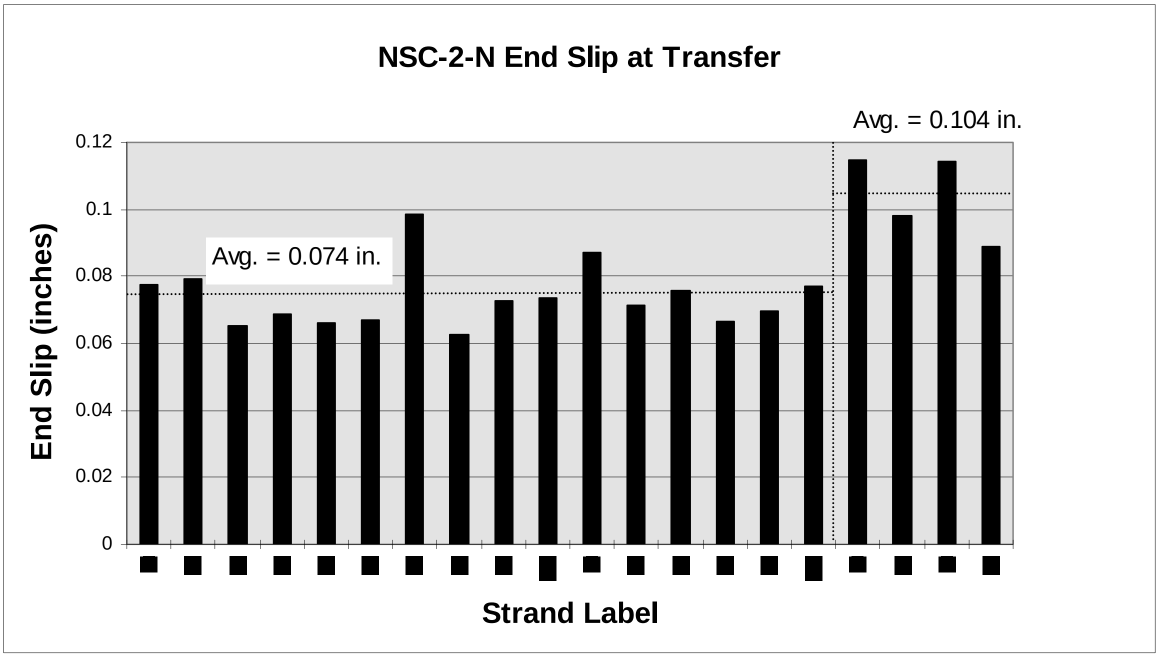

Fig. D-7 End slip of beam end NSC-2-N at transfer

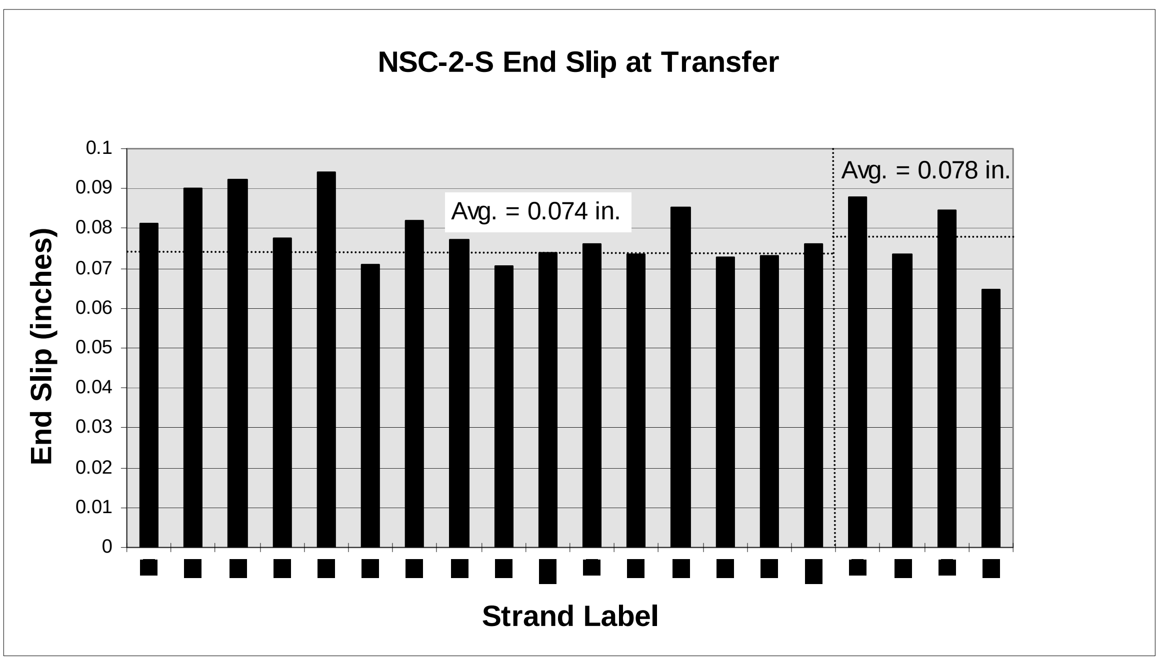

Fig. D-8 End slip of beam end NSC-2-S at transfer

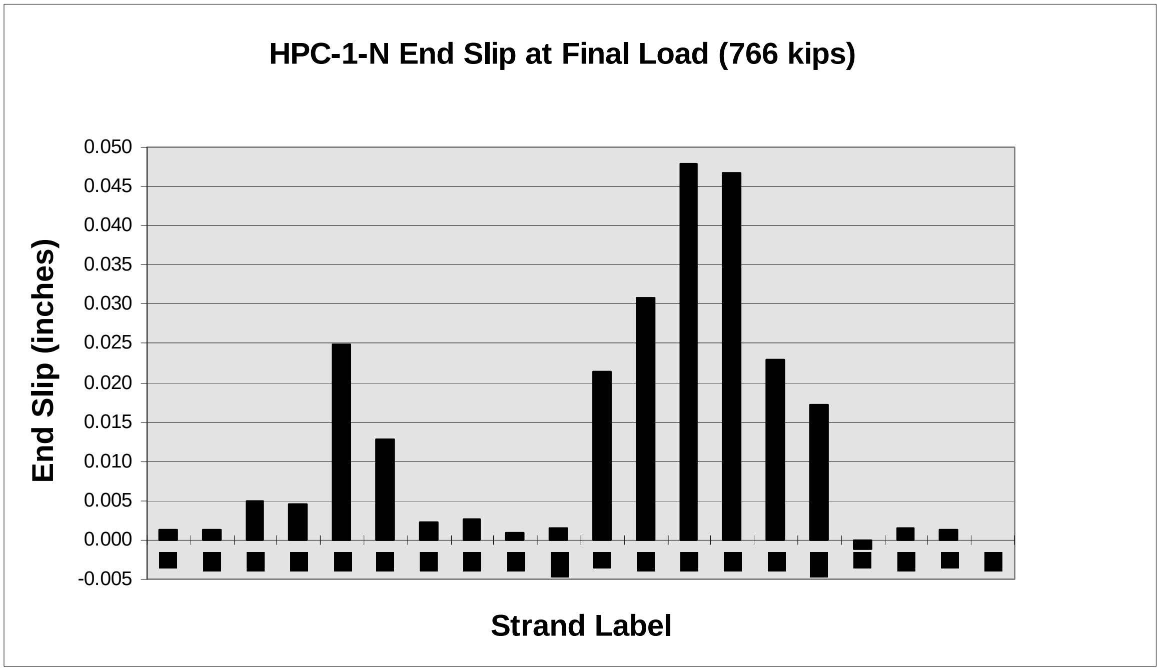

Fig. D-9 End slip of beam end HPC-1-N after development length test

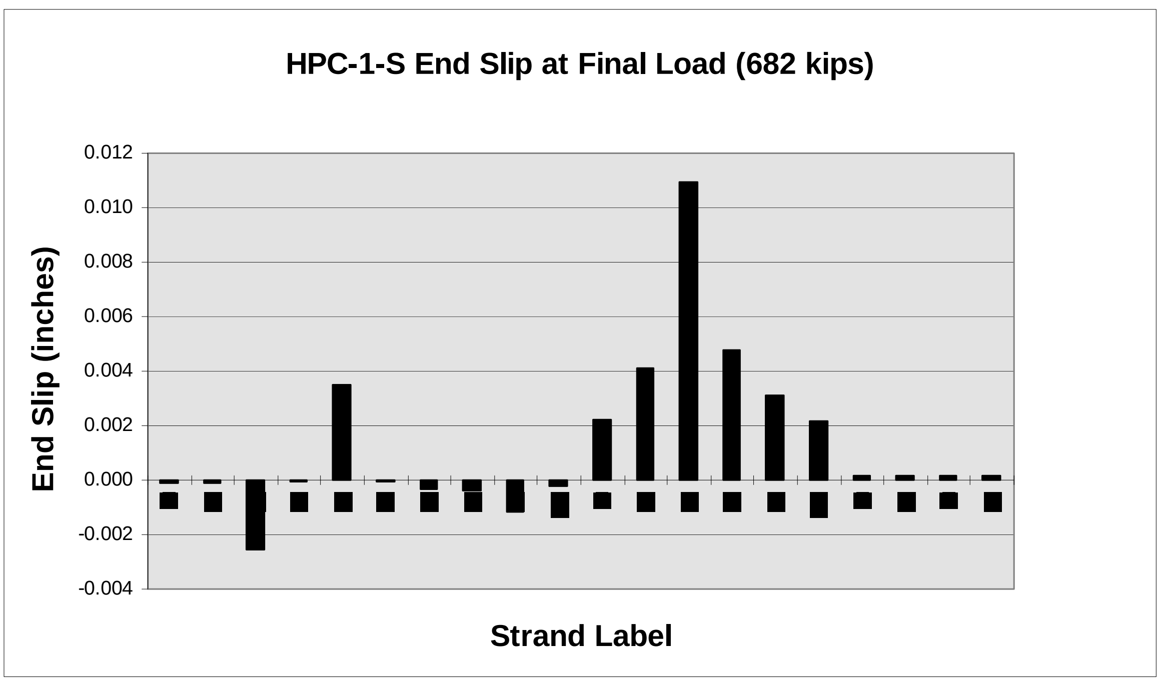

Fig. D-10 End slip of beam end HPC-1-S after development length test

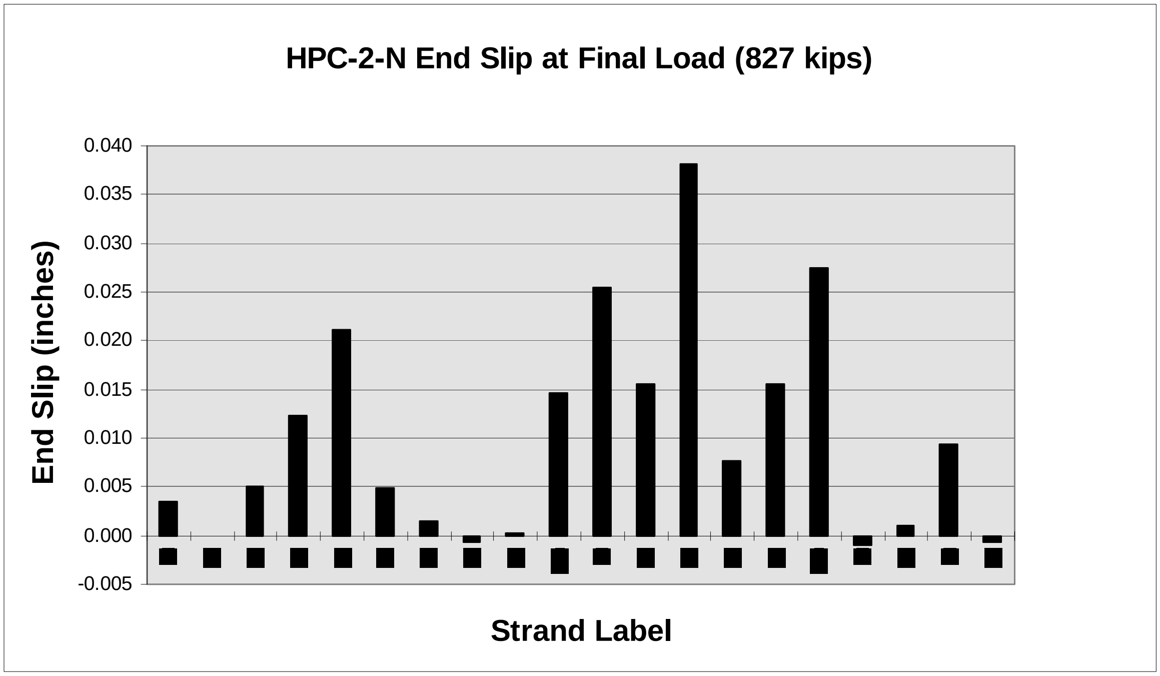

Fig. D-11 End slip of beam end HPC-2-N after development length test

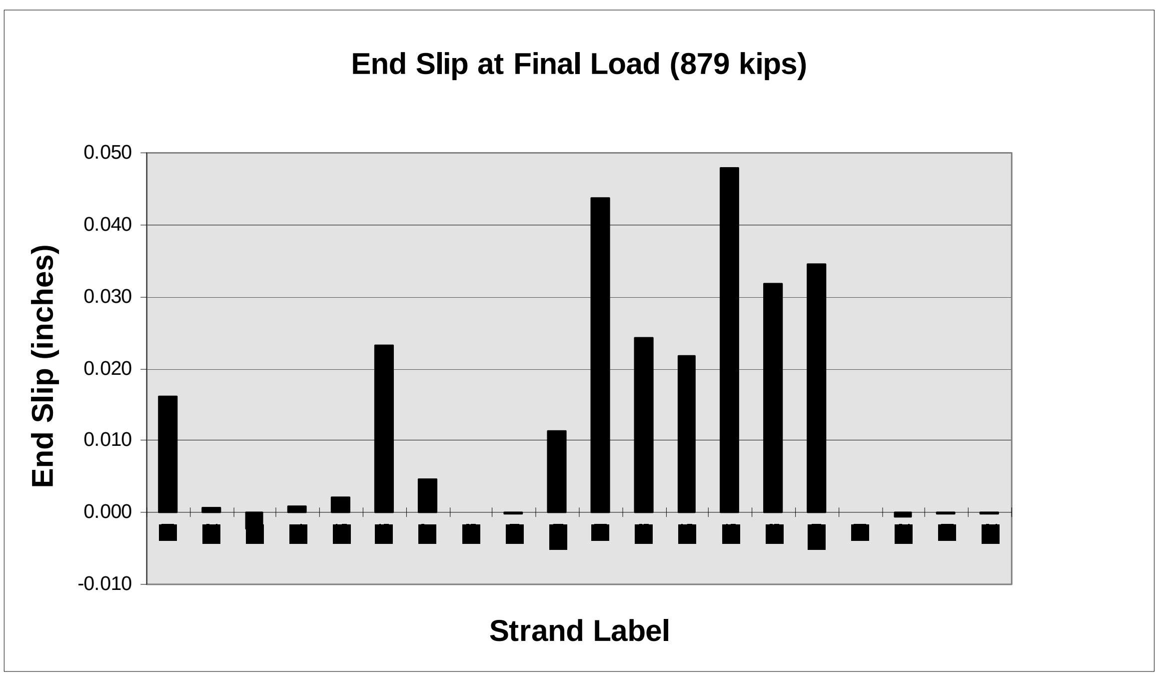

Fig. D-12 End slip of beam end HPC-2-S after development length test

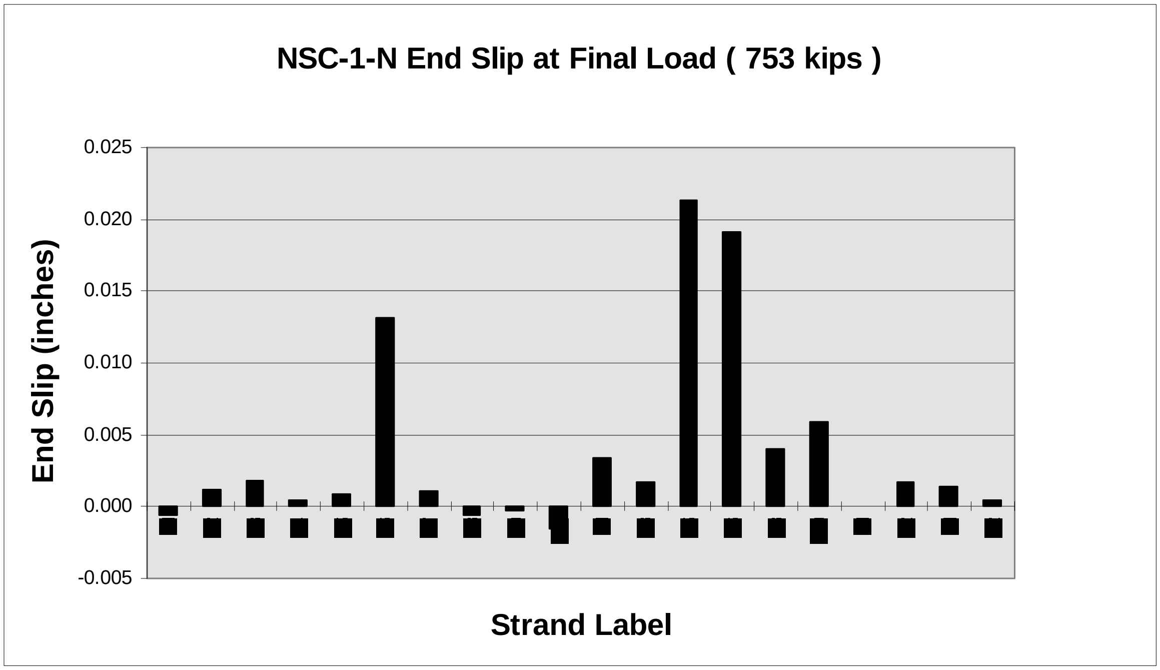

Fig. D-13 End slip of beam end NSC-1-N after development length test

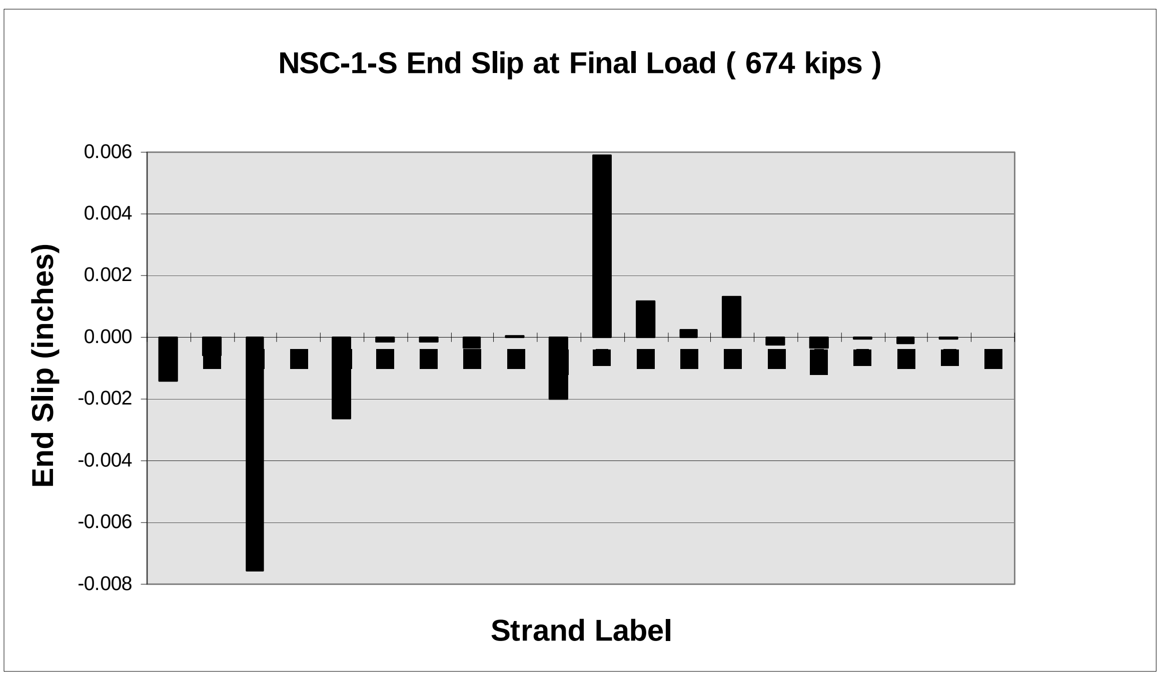

Fig. D-14 End slip of beam end NSC-1-S after development length test

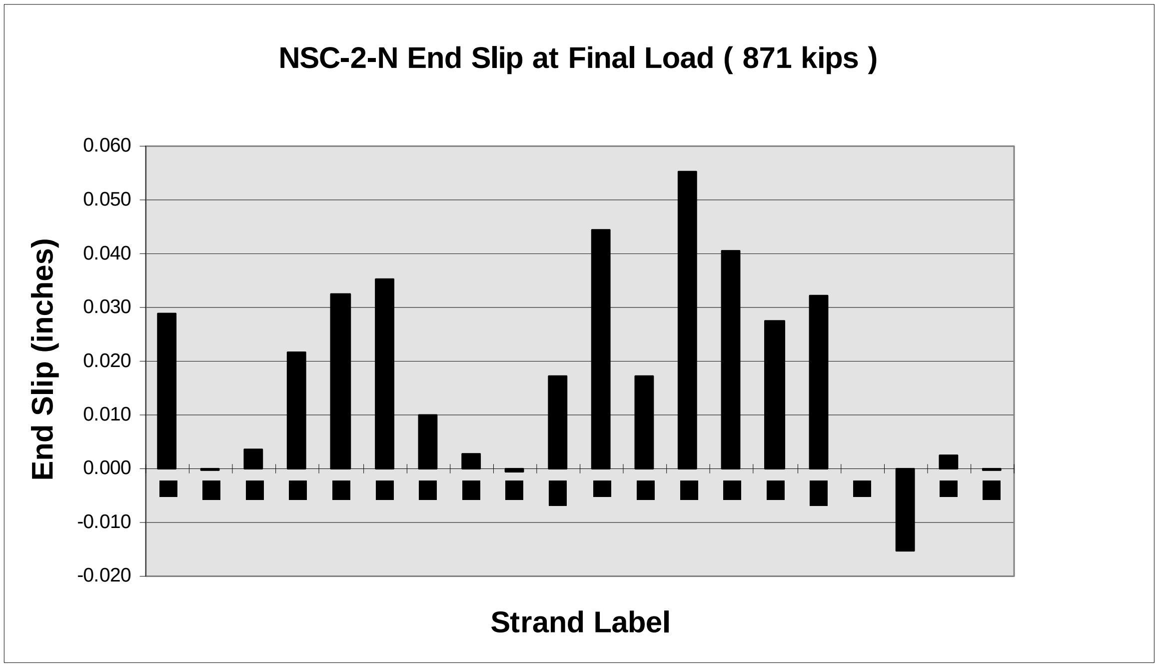

Fig. D-15 End slip of beam end NSC-2-N after development length test

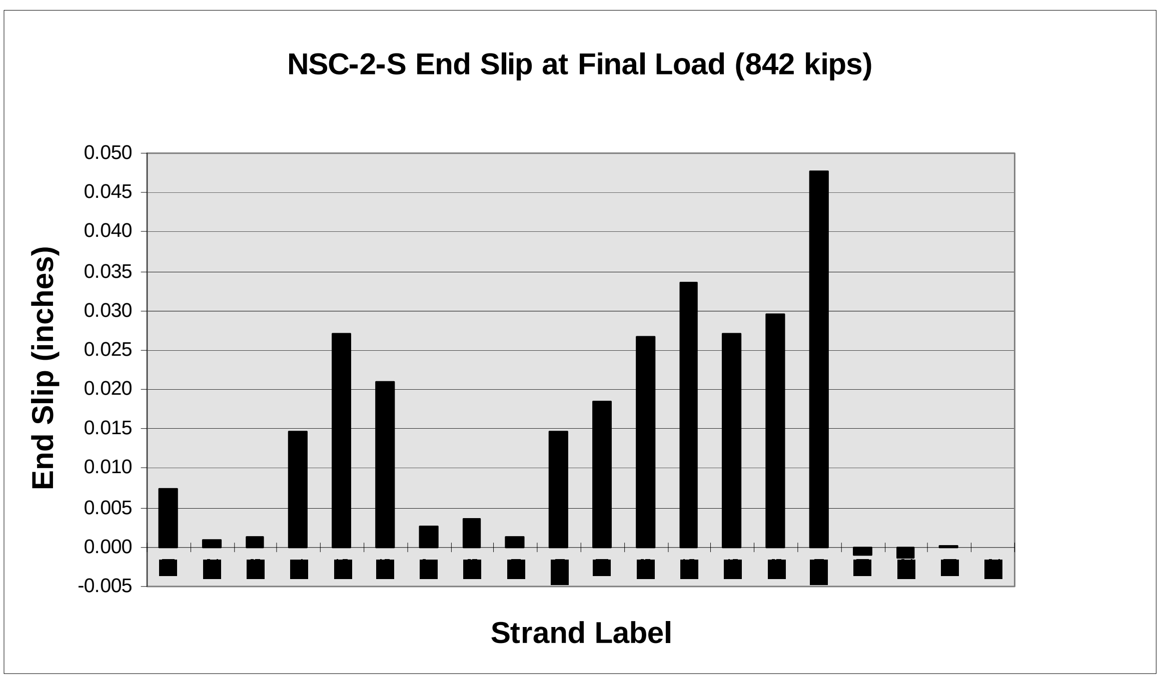

Fig. D-16 End slip of beam end NSC-2-S after development length test

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