BOND AND MATERIAL PROPERTIES OF GRADE 270 AND GRADE 300 PRESTRESSING STRANDS

by

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ABSTRACT

The first objective of this thesis was to determine the material properties of grade 270 and grade 300 prestressing strand of various sizes. Tension tests were performed on each type of strand. The data from these tests was used to determine modulus of elasticity, yield stress, ultimate stress, and ultimate elongation for each strand. The yield stresses and ultimate stresses for many of the strands did not meet the requirements found in ASTM A416. The ultimate elongation results far exceeded the requirements and the measured elastic moduli were near the modulus recommended by AASHTO LRFD. A secondary objective from the tension tests was to evaluate a gripping method which used aluminum tubing to cushion the strands against notching. The grips performed very well. Most of the strand breaks did not occur in the grips and when a strand did break in the grips, the failure occurred after significant post-yield elongation.

The second objective was to evaluate the bond properties of grade 270 and grade 300 prestressing strands. The North American Strand Producers (NASP) Bond Test and Large Block Pullout Test (LBPT) were performed on six different strand grade and strand size combinations. Both of the tests are simple pullout tests on untensioned strand. The results for each strand type were compared to one another as well as to measured transfer and development lengths from beams using the strand from the same reel. All of the strands showed sufficient bond in the beams, but one strand type did fail both the NASP Test and the LBPT. Both pullout tests were acceptable methods to evaluate strand surface condition and the benchmarks set for 0.5 in.

diameter regular strand were conservative for the strands used in this thesis. Little difference was evident in the bond performance of grade 270 and grade 300 prestressing strand. All of the images in this thesis were taken or created by the author between the dates of January 1, 2007 and June 10, 2008.

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1. INTRODUCTION

1.1 Background

Prestressed concrete gained popularity mainly due to a material shortage during WWII. The studies of Eugene Feyssinet first made prestressed concrete a practical solution in the 1930's through the use of high strength steel and high strength concrete. One of Feyssinet's first designs was the Luzancy bridge—an impressive 180 ft concrete arch over the Marne River in France (Nilson 1987).

In prestressed concrete, a compressive force is applied to the member before service loads to help counteract the weak tensile properties of concrete. By limiting or eliminating the tensile stresses in the concrete, the engineer can control cracking in the member. Deflections are reduced by the stiffer, uncracked section and by the initial camber of the member. Prestressed concrete permits a more efficient design through the use of high strength steel and concrete. Also, it increases the viability of precast members, which can reduce construction times and costs.

Prestressed concrete can be divided into two categories depending on when the prestressing force is applied. Post-tensioning is done by casting ducts into the concrete, and stressing strands placed in the ducts. In many cases, he ducts are then filled with grout. The other prestressing technique widely in use today is pretensioning. Pretensioning is a method in which concrete is cast around seven-wire strand tensioned between two stiff anchorages. The concrete is cured to the desired strength, and the stress in the strand is then transferred to the concrete (Nilson 1987).

The seven-wire strand commonly used in pretensioning applications consists of a straight center wire with six other wires helically wrapped around it. ASTM A416 *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete* (2005) outlines the required material properties for seven-wire stand. Prestressing strand is labeled by a grade and a size, which in turn provides the force it can hold. The grade of the strand represents the stress the strand is guaranteed to sustain before rupture. Currently, grade 270 0.5 in. diameter regular strand is the industry standard, which has a cross-sectional area of 0.153 in.^{2} The two other strand sizes most commonly used are 0.5 in. diameter super stand and 0.5 in. diameter strand, which have cross-sectional areas of 0.167 and 0.217 in.^{2}, respectively. Grade 300 strand has recently been developed and offers the opportunity to increase the prestressing force without increasing the amount of steel required. Stronger strand also allows an engineer to take full advantage of high performance concrete.

1.2 Objectives

This thesis is part of a project funded by Virginia Department of Transportation (VDOT) and Virginia Transportation Research Council (VTRC) to investigate the performance of the new grade 300 prestressing strand. All of the testing for this thesis was performed at the Virginia Tech Structures and Materials Laboratory. This thesis will focus on two main objectives: the material properties and the bond characteristics of this higher strength prestressing strand. Grade 270 strand, which is already widely in use, is used as a control.

1.2.1 Material Properties

The first objective of this thesis is to investigate the material properties of grade 270 and grade 300 prestressing strand. The relationship between stress and strain in prestressing strand is an integral part of prestressed concrete design and in predicting the behavior of a prestressed concrete element. The results of tension tests were used to determine the modulus of elasticity, yield stress, ultimate stress, and ultimate elongation of seven different types of strand. The six samples consist of three sizes and two grades. The three sizes are 0.5 in. diameter regular strand, 0.5 in. diameter super strand, and 0.6 in. diameter strand. Grade 300 0.6 in. strand is not currently in production and was not investigated. Grade 300 0.5 in. regular strand from two manufacturers was used in the tension tests.

1.2.2 Bond Properties

The second objective of this thesis is to investigate the bond between concrete and prestressing strand for grade 270 and grade 300 strand. The ability of the concrete to bond with the strand affects and is evident from the transfer and development length of the prestressing strand. The surface condition of the strand has a great impact on the strand's ability to bond with concrete. ACI 318 (2005) states that slightly rusted strand can have much shorter transfer lengths than a bright strand. In addition, latent lubricants, cleaning solvents, or other substances on the surface of the strand can diminish the bond between the concrete and steel.

The large block pullout test (LBPT) and the North American Strand Producers (NASP) Bond Test evaluate the surface condition of prestressing strand. The LBPT was originally developed by Moustafa in the 1970's and was modified by Logan (1997). The NASP Test was recently developed by Russell and is outlined in a report to the National Cooperative Highway Research Program (Ramirez and Russell 2007) and is also described by Mote (2001). The results of the LBPT and NASP Tests performed as part of this thesis will be used to compare the bonding characteristics of grade 270 and grade 300 prestressing strand. The results will also be compared with the results from flexural tests performed previously in this project (Hodges 2006) to assess the ability of the LBPT and NASP Bond Test to evaluate bonding characteristics and the validity of the tests as standards.

1.3 Thesis Organization

This thesis is divided into five chapters. Chapter 1 introduces the subject and states the objectives of the research. Chapter 2 is a literature review of code provisions and past research that discuss the material properties, transfer length, development length, and pull-out tests of prestressing strand. The procedure and test setup used in the pull-out tests and the tensile tests is explained in Chapter 3. Chapter 4 presents the results of the testing as well as analysis and discussion of the results. Finally, Chapter 5 presents a summary of the research, conclusions, and recommendations for further research.

2. LITERATURE REVIEW

2.1 Material Properties

The source of the precompression in prestensioned concrete members is prestressing strand. While similar in molecular structure to mild steel, prestressing steel exhibits a significantly different stress-strain behavior. Strand does not have a yield plateau but instead its stress-strain curve is almost bilinear. A typical stress-strain relationship for the industry standard grade 270 strand is shown below in Figure 2.1. While much research has been done on grade 270 strand material properties, little has been done on grade 300 strand. As a result, ASTM A416 (2005) regulates the properties of grade 250 and grade 270 strand, but does not yet have provisions for grade 300 strand. ASTM A416 states that the ultimate stress for grade 270 strand for all valid tests must greater than 270 ksi. The yield stress is taken as the stress at 1 percent extension from an initial load of 10 percent of ultimate. The stress at this extension must be above 90 percent of the required ultimate stress, which is 243 ksi and 270 ksi for grade 270 and grade 300 strand, respectively. Finally, the maximum measured strain in the strand must be at least 3.5 percent. The modulus of elasticity is not regulated by ASTM A416.

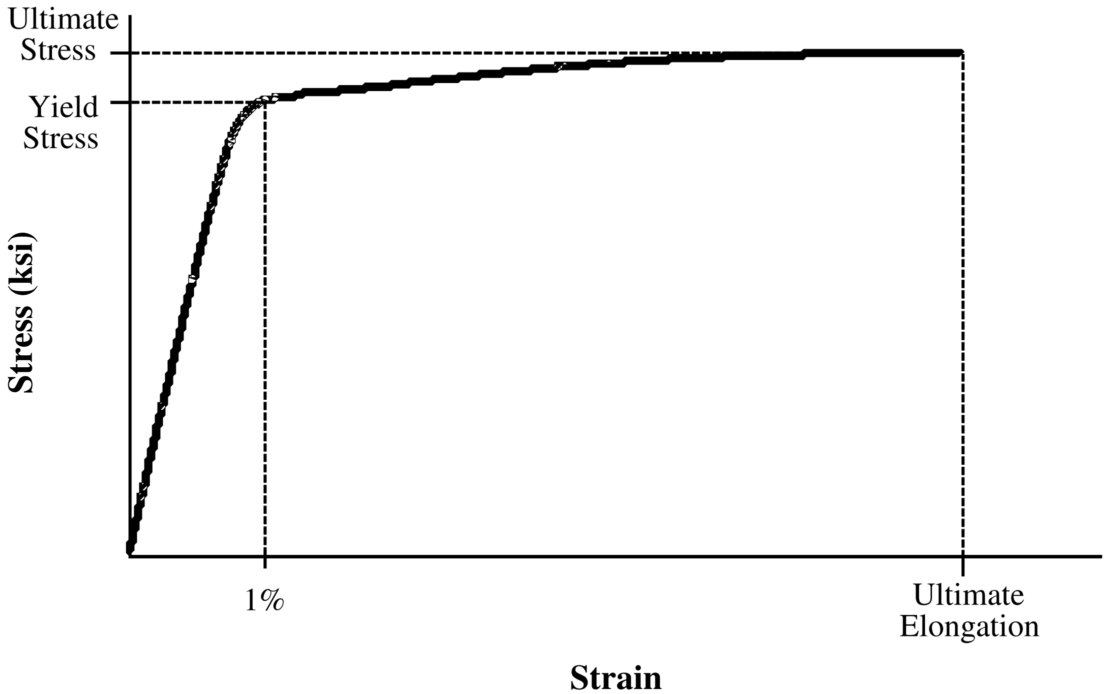

Figure 2.1 Typical Stress-Strain Profile for Prestressing Strand

2.1.1 Strand Production and Testing Techniques

Prestressing strand is made from the same raw materials as normal reinforcing steel. They both contain iron, carbon, manganese, and silicon. Prestressing steel, however, contains about 4 to 5 times as much carbon as normal reinforcing steel (Godfrey 1956). The wires used in strands start out as high strength steel rods. The rods are subjected to a heat treatment called patenting, which enhances the steel's strength and ductility. The rods are then passed through a series of dies which lengthen and reduce the area of the rods. This coldworking process greatly increases the ultimate and yield strength. The wires made from this process are then used to produce prestressing strand. In seven-wire strand, six outer wires are wrapped around a larger center wire (Podolny 1967). Due to the drawing and wrapping processes the wires contain a large amount of residual stresses. To remove these residual stresses, the strands are heated through induction. Low-relaxation strand is tensioned while heated which results in a one percent permanent elongation and a large reduction in potential relaxation losses (Preston 1990).

Because grade 300 prestressing strand is a recent development in the industry, few tests have been done to investigate its material properties. One of the purposes of this thesis is to investigate the material properties of grade 300 prestressing strand through tensile tests on strand specimens. One of the major problems encountered in tension tests is strand notching. High carbon steels are much more notch sensitive than normal steel. The potential for premature failure at the location of the gripping device caused by notching has been noted by a number of researchers including Godfrey (1957), Podolny (1967), Preston (1990 and 1985), Devalapura and Tadros (1992), and Hill (2006). ASTM A370 (2005) states that a test that fails in the grips is valid only if it meets the minimum strength and ductility requirements. Because of the strands' vulnerability to notching, a special gripping method must be used. Several methods are listed by Preston (1985) and in ASTM A370 *Standard Test Methods and Definitions for Mechanical Testing of Steel Products* (2005). One of the suggested methods is the aluminum insert method. A similar method using aluminum tubing to help reduce the risk of notching was used in the research for this thesis.

2.1.2 Hill

The primary objective of the research by Hill (2006) was to determine the material properties of grade 300 prestressing strand. Also, as a secondary objective two methods for gripping prestressing strand during tensile tests were evaluated. Relaxation tests were performed by tensioning the strand to between 50 and 80 percent of ultimate stress in frames with three different lengths. Tensile tests were done on both grade 270 and grade 300 0.5 in. regular strand

and 0.5 in. super strand and on grade 270 0.6 in. strand. The first gripping method was wrapping aluminum foil around the strand, and the second was attaching aluminum tubing to the strand using an aluminum oxide grit and epoxy mix. Strain output from a 2 in. extensometer was used along with load output to determine modulus of elasticity, yield stress, ultimate stress, and ultimate elongation.

All of the strands tested had relaxation losses less than the minimum required by ASTM A416 of 2.5 percent. The average relaxations for grade 270 and grade 300 0.5 in. diameter regular strands were 1.51 and 1.34 percent. The relaxation losses for super strands were 1.30 and 1.80 percent for grade 270 and grade 300 super strands, respectively. These losses are well below the minimum from ASTM A416 and are near the 1.52 percent predicted loss from 2005 AASHTO LRFD. The total average losses for grade 270 and grade 300 strands were 1.57 and 1.59 percent, respectively, which indicates that there is virtually no difference in the relaxation properties of the two strengths of strand. Grade 270 0.6 in. diameter strand had the highest measured losses with an average loss of 2.35 percent.

The author (Hill 2006) found that all the strands surpassed the minimum required breaking stress in all valid tests. The ultimate stress results of the two grades for both 0.5 in. sizes were almost identical. The 0.5 in. regular strands were both an average of about 7 percent higher than minimum breaking strength and the 0.5 in. super strands were about 12 percent higher. The grade 270 0.6 in. strands were also about 12 percent over minimum breaking strength. In all cases, the gripping method had a significant influence on the results. In many of the tests using aluminum foil, the strands broke prematurely in the grips and the results were discarded because the values did not surpass the ASTM A416 requirements. Strands tested with the aluminum tubing had a much lower likelihood of breaking in the grips than strand tested using aluminum foil as cushioning material.

The researcher found yield stress results similar to the results of the ultimate stress. Every specimen had a measured yield stress higher than the required stress, which is 90 percent of the minimum breaking stress. While the gripping method did have some effect on the yield results, its effect was not as evident as it was for the ultimate stress. The modulus of elasticity was virtually identical for the grade 270 and grade 300 strands. The grips had little effect on the modulus; however, the tests using the aluminum foil grips had a modulus slightly higher than the special aluminum insert grips. All of the specimens tested had breaking elongations that exceeded the required ultimate elongation in ASTM A416 of 3.5 percent. The average of each type of strand was more than double the required elongation, except for the grade 270 0.6 in. strand which had an average elongation of 6.8 percent. The grips had an effect on the ultimate elongations as well. The strands gripped with the aluminum inserts averaged 7.5 percent elongation while the strands gripped with aluminum foil averaged 6.8 percent elongation. Finally, the author concluded that while aluminum foil provided enough cushion for the 0.5 in regular strands, aluminum tubing proved a much better gripping method for the two larger strand sizes (Hill 2006).

2.1.3 Devalapura and Tadros

The researchers in this study (Devalapura and Tadros 1992) performed tensile tests on 28 strand samples from four different strand producers. All of the strand samples were grade 270, low relaxation 0.5 in. diameter strands. The researchers used aluminum angles to provide a cushion between the grips and the strands in order to prevent premature breaks due to stress concentrations in the grips. The authors also collected 28 stress-strain curves from six different strand manufacturers. The following power formula was used to develop a prediction equation for the stress-strain curve of prestressing steel:

$$f_{ps} = \varepsilon_{ps}\left[A + \frac{B}{\left(1+\left(C\varepsilon_{ps}\right)^{D}\right)^{1/D}}\right] \leq f_{pu} \qquad \text{2-1}$$

Where:

f_{ps} = stress in the strand (ksi)

ε_{ps} = strain in the strand

A, B, C, D = constants used in power formula

f_{pu} = specified tensile strength of strand (ksi)

The authors solved for constants in Equation 2-1 that would establish a lower bound to the 56 sets of stress-strain data they had collected. They also placed a boundary of 243 ksi at one percent elongation and capped the stress at 270 ksi. Both of these stresses were used because they are the specified minimums in ASTM A416. The researchers found that for their data and for their given boundary conditions, the constants *A, B, C*, and *D* were equal to 887, 27613, 112.4, and 7.360, respectively (Devalapura and Tadros 1992).

2.2 Transfer and Development Length

2.2.1 Code Provisions

ACI 318 (2005) uses a bilinear model for the development length. The relationship used is found in Section 12.9.1 and can be seen in Equation 2-2 below:

$$\ell_d = \left(\frac{f_{se}}{3000}\right)d_b + \left(\frac{f_{ps} - f_{se}}{1000}\right)d_b \qquad \text{2-2}$$

Where:

ℓ_d = development length (in.)

f_{se} = effective stress in prestressing steel (psi)

d_b = nominal diameter of prestressing strand (in.)

f_{ps} = stress in prestressing strand at nominal flexural strength (psi)

The ACI 318-05 Commentary (2005) states that the first term of this equation represents the transfer length, which is the length over which the effective prestress is developed in the prestressing strand. The equation assumes a linear transfer of stress from the strand to the concrete as shown in Figure 2.2. The second term in Equation 2-2 represents the flexural bond length. This length is the additional length needed to develop the stress in the strand at the member's nominal flexural strength. ACI Section 12.9.1 states that the development length given by Equation 2-2 is the minimum length the prestressing steel must be embedded in concrete from the critical section. However, the embedment length is permitted to be less than ℓ_d if the required stress in the strand is less than the stress calculated using a bilinear relationship. The stress varies from zero at the end of the member to the effective prestress at the end of the transfer length and then varies linearly from the effective prestress to the stress at nominal strength over the flexural bond length. This relationship is shown below in Figure 2.2.

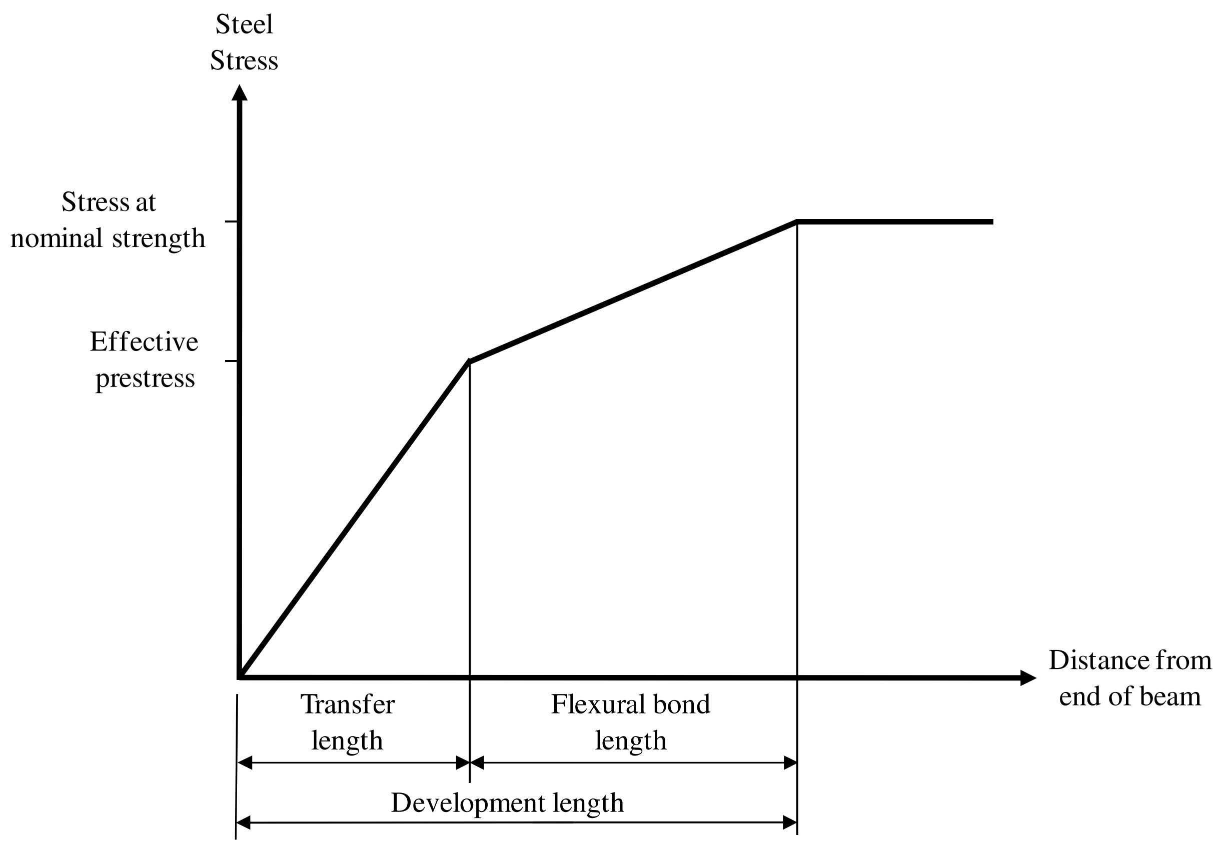

Figure 2.2 Idealized bilinear relationship between strand stress and distance from end of beam

ACI 318 provides a second method to estimate transfer length which is used for shear design in Section 11.4.4. The prestress force is assumed to vary linearly from zero at the end of the member to the full effective prestress force at 50 strand diameters from the end of the member. This transfer length can be obtained from Equation 2-2. If one assumes Grade 270 strand stressed to 75 percent of the guaranteed ultimate strength with 25 percent losses, the effective prestress is about 150,000 psi, which would give a 50 strand diameter transfer length from Equation 2-2

2-2 (ACI 2005). Using the same assumptions with grade 300 strand yields a transfer length of approximately 55 strand diameters. It should be noted that neither of the methods prescribed in ACI 318 account for strand surface condition. As indicated in studies by Rose and

Russell (1997) and Logan (1997), strand surface condition can have a significant impact on the transfer and development length of prestressing strand. The pullout tests performed as part of this thesis provide further data on the relationship between surface condition and transfer and development lengths.

The provisions from AASHTO LRFD Design Specifications (2006) are similar to those provided by ACI. In Article 5.11.4.1 AASHTO defines the transfer length as 60 strand diameters. The equation used to calculate the development length is found in Article 5.11.4.2 and is shown below:

$$l_d \geq \kappa\left(f_{ps} - \frac{2}{3} f_{pe}\right)d_b \qquad \text{2-3}$$

Where:

l_d = development length (in.)

κ = 1.0 for pretensioned members with depth less than or equal to 24.0 in.

κ = 1.6 for pretensioned members with depth greater than 24.0 in.

f_{ps} = average stress in prestressing steel required for nominal resistance (ksi)

f_{pe} = effective stress in prestressing steel after losses (ksi)

d_b = nominal strand diameter (in.)

The multiplier κ was inserted because research by Cousins (1986) indicated that Equation 2-3 was unconservative in some cases without the multiplier. As a result of the unconservative results, AASHTO increased the calculated development lengths of strands by 60 percent. With κ equal to 1.0, Equation 2-3 is the same as Equation 2-2 found in ACI 318. AASHTO also uses the bilinear relationship between strand stress and embedment length as shown in Figure 2.2. The stress in the strand varies from zero at the free end of the strand to the effective prestress at the end of the 60 strand diameter transfer length. The strand stress varies linearly between the effective prestress and the stress required for nominal moment capacity over flexural bond length (AASHTO 2006). Similar to ACI, the AASHTO equations have no way to account for strand surface condition. While the 60 percent increase to development length may make Equation 2-3 conservative for most surface conditions, the method for transfer length estimation has no such multiplier.

2.2.2 Hodges

The purpose of this study (Hodges 2006) was to investigate the effects of casting orientation on the bond quality of grade 270 and grade 300 prestressing strands and to compare measured effective prestress to theoretical values. Twelve 24 ft long tee-shaped beams were cast in four pours at the Virginia Tech Structures and Materials Laboratory. Each pour had one prestressing bed for grade 270 strands and another bed for grade 300 strands. In each prestressing line one beam was cast right side up and another was cast upside down. The researcher used 0.5 in. regular strands in half of the beams and 0.5 in. super strands in the other half. A larger cross section was used for the larger strands. Each beam contained three strands, spaced at 2 in. on center and located 2 in. from the bottom of the web. The strands were stressed to 67 percent of ultimate strength. Concrete with a target 28-day strength of 6000 psi was poured and moist-cured for 7 days. The prestress was transferred by flame cutting the strands between the beams after the concrete reached a minimum compressive strength of 4500 psi. Concrete surface strains were measured using gauge points placed on the concrete surface after stripping the formwork. The gauge points were spaced at 3.94 in. near the beginning and end of the transfer zones and at 1.97 in. near the center of the zone. A 7.87 in. strain gauge was used to measure the elongation or contraction between the gauge points. Strain readings were made immediately after transfer and one to two weeks after transfer.

The transfer length was determined using the 95 percent average maximum strain method. The results of the transfer and development length tests, shown below in Table 2.1, were compared to the results of the two pullout tests performed with this thesis.

Table 2.1 Transfer and Development Lengths from Hodges

Strand Type	Casting Orientation	Development Length (in.)		Final Transfer Length (in.)	
		Minimum	Maximum	Minimum	Maximum
Regular Grade 270	Normal	No Data	66.5	13	19.5
	Inverted	63	No Data	27	30
Regular Grade 300	Normal	42	66	15	21
	Inverted	60	No Data	24.5	44
Special Grade 270	Normal	49.5	69.5	14	22.5
	Inverted	53.5	78.5	22	28.5
Special Grade 300	Normal	62	76	16	20
	Inverted	42.5	89.5	23.5	41

Only four of the 23 measured transfer lengths exceeded the ACI provision of 50 strand diameters, and only two exceeded the AASHTO recommended 60 strand diameters. The transfer length for grade 300 strands averaged 12 percent longer than the transfer length of grade 270 strands. The initial prestress force of the grade 300 strands averaged 12 percent higher than the initial prestress in grade 270 strands. However, three of the eleven head to head comparisons had measured transfer lengths of grade 300 strand that were less than that of grade 270 strand. Casting orientation had a noticeable effect on the transfer length. The upside down beams had an average transfer length 69 percent longer than right side up beams, and two of the upside down beams had a measured transfer length twice as long as their companion right side up beams.

The development length of the strand was investigated by loading the beams to failure with a point load at varying lengths from the ends of the beam. The beams were loaded on a 16 ft span so that each end of the beam could be tested separately. The tips of the strands were monitored with LVDT's. If the strands slipped more than 0.01 in. before the concrete crushed or the strands ruptured due to flexure, the test was considered a bond failure and the next test was conducted with the load farther from the end of the beam. If the beam failed in flexure then the next test was conducted closer to the end of the beam. The development length lies between the longest embedment length at which a bond failure occurred and the shortest embedment length at which a flexural failure occurred. Three to four tests were performed for each strand type on normally cast beams and two tests were performed for each strand type on beams cast upside down.

The results of the flexural tests can be seen in Table 2.1. From the results the author formulated a range for development length and flexural bond length. The grade of strand exhibited little effect on the development lengths of 0.5 in. normal strands in either casting position or in 0.5 in. special strands cast upside down. The development length of grade 300 0.5 in. special strands cast normally was significantly higher than that for grade 300 0.5 in normal strands. Finally, casting orientation had a significant effect on the development lengths of all strand types (Hodges 2006).

The strand used by Hodges came from the same reels as the strand used in the tension and pullout tests associated with this thesis. The results of the Large Block Pullout Tests and NASP Bond Tests will be compared to Hodges' results as well as results from transfer and development length tests performed later in this project. This comparison will help determine how well the pullout tests can be associated with the ability of the strand to bond with concrete in practice.

2.3 North American Strand Producers (NASP) Bond Test

2.3.1 Mote

The researcher in this study (Mote 2001) examined the effect of several variables on bond performance and formulated a model using these variables to predict bond quality. The effects of confining pressure, concrete strength, concrete age, strand source, specimen geometry, and strand surface condition were examined. The researcher performed Friction Bond Tests, Tension Prism Tests, North American Strand Producers (NASP) Bond Test, and Moustafa Pullout Tests. The Moustafa Pullout tests will be discussed in more detail later in this literature review. Strand was collected from three different manufacturers and tested in the as-received condition. The three manufacturers were labeled A, D, and F.

The Friction Bond Tests consisted of a 6 in. cube with a strand through the center. The strand was debonded for 1.5 in. from each edge producing a 3 in. embedment length. Four different concrete mixes were used for the specimens with target compressive strengths ranging from 3000 psi to 11,000 psi. Confining pressures of 0, 250, 500, and 1,000 psi were applied to the sides of the cube. Load was applied to the strand with a hydraulic actuator and the free end slip was recorded using a linear variable differential transformer.

The Tension Prism specimens were 60 in. long and had a 3, 4, or 5 in. square cross section. Two concrete mixes were used with target strengths of 7000 to 7500 psi and 10,000 to 11,000 psi. The strand protruded out both ends of the specimen. The specimen was placed in a frame and the strand tensioned until the concrete cracked. The crack was marked and the specimen was loaded until another crack formed. This process was repeated until 40 kips or the strand ruptured.

The NASP test consisted of an 18 in. long, 5 in. diameter tube with a 16 gage wall thickness. A 1/4 in. by 6 in. by 6 in. steel base plate was welded to one end of the tube to close the form for concrete placement and to facilitate strand loading. A strand passed through the center of the tube and through a 9/16 in. hole in the plate. A 2 in. duct tape bond breaker was placed on the strand at the bottom of the specimen to reduce the effects of confinement. A mortar mix with a target strength of 3000 to 4000 psi was placed in the tube and cured for 24 hours. The tests were displacement controlled with a 0.10 in./minute stroke rate. The strand slip at the top of the specimen was monitored with an LVDT. The specimen design and test procedure used by Mote is nearly identical to that used for the NASP tests in this thesis.

Strand source was found to have a significant effect on all the performed tests. The effect was less evident in the NASP tests than in the other three tests although a definite trend existed. Strand A and D consistently performed well in the respect that after first slip occurred the load in the strand increased while the maximum load in strand F occurred at or shortly after first slip. In most of the tests the load sustained by strand F actually decreased after first slip. This trend is clearly evident in the summarized NASP test results seen in Table 2.2 below:

Table 2.2 Average NASP and Moustafa Test Results from Mote

Strand	Pull-out Force (kips)			
	NASP Tests			Moustafa Tests
	0.01 in. slip	0.1 in. slip	Maximum	
A	7.65	8.34	9.23	30.51
D	7.88	9.00	11.02	34.39
F	7.92	7.22	7.97	25.62

The effect of concrete strength was investigated in the Friction Bond Tests. An increased concrete strength improved bond for all the types of strand and had a greater effect at higher values of slip. Through a regression analysis the researcher found that an increase of concrete compressive strength of 1000 psi would increase the bond strength from an average of 79 to 130 lbs/in. depending on the increment of slip. Concrete age did not appear to affect the bond quality of prestressing strand (Mote 2001).

2.3.2 Ramirez and Russell

In this study, Ramirez and Russell (2007) sought to further develop a standardized test for strand bond quality called the NASP Test. The researchers assessed the feasibility of the test as a standard by investigating the repeatability of the test and by comparing the results of the NASP Test to results from transfer and development length tests performed with the same strand. The protocols listed by the authors in the appendix were used to perform the NASP Tests associated with this thesis.

The test consisted of an 18 in. long, 5 in. diameter steel tube with a prestressing strand cast concentrically in the tube with a cement-sand mortar. To develop the test, the researchers used a mortar mix with 24 hr compressive strengths varying between 3500 and 5000 psi. The results for the different concrete strengths were too variable, so the researchers limited the mortar strength in the test standard to 4500 to 5000 psi. The researchers also set a flow requirement between 100 and 125 to ensure consistent consolidation of the grout. Furthermore, as a result of earlier testing, the load corresponding to 0.1 in. of slip was found to vary the least between individual tests, and this load was adopted as the value by which the strands' bond quality would be judged.

In addition to the mortar mentioned above, the researcher also used concrete in NASP Tests. The tests with concrete were used to investigate the effect of compressive strength on bond quality and the results of the NASP Tests. The compressive strengths of the concrete varied between 4000 and 10,000 psi. The concentrically cast strand was pulled at a displacement rate of 0.10 in./min, but the authors also recommend a maximum load rate of 8000 lb/min for 0.5 in. diameter strands and 9600 lb/min for 0.6 in. diameter strands. Free end strand slip and load were monitored for each test. Two strand sizes and seven strand producers were used in the testing: six 0.5 in. diameter strand labeled A, AA, B, D, HH, and II and one 0.6 in. diameter strand labeled A6. All strands used were grade 270.

The transfer and development length tests were performed on rectangular and I-shaped beams. The concrete used in the beams had target release strengths between 4000 and 10,000 psi. The rectangular beams were prestressed with either two or four strands. Those with two strands cast in the bottom of the cross section were used for both tests and those with two strands cast in the top and bottom were used for only transfer length tests. The I-shaped members were stressed with one strand in the top and three or four strands in the bottom for 0.5 in. diameter strand and 0.6 in. diameter strand, respectively. Transfer lengths were measured using both end slip and concrete surface strains. In the development length testing, the beams were tested with a concentrated load at a 73 in. and 58 in. embedment length, which are the development length and 80 percent of the development length calculated from AASHTO LRFD.

NASP Tests were performed at two sites. When plotted against a line that represented the same recorded value at each site, the results had a correlation coefficient of 0.96. Because of the results' similarities, the researchers concluded that the test exhibited repeatability. The researchers found that both the NASP Test values and the transfer lengths were proportional to the square root of the concrete's compressive strength. The effect of concrete strength on development length was also evident. Beams with higher strength concrete failed in flexure at the same or lesser embedment lengths than those beams with lower strength concretes that had a bond failure.

The NASP Bond Test values of strands A and B were virtually identical with an average value of around 20 kips while strand D had a significantly lower pullout value of 6.6 kips. The transfer and development length tests showed similar results. Strand D had average transfer lengths around 40 percent longer than the average transfer lengths for Strands A and B. Transfer lengths were not given for strands AA, HH, or II. The authors develop the following relationship between transfer length and the NASP pullout value for 0.5 in. diameter strands:

$$l_t = \frac{97.2}{\sqrt{NASP}} \qquad \text{2-4}$$

Where:

l_t = transfer length (in.)

$NASP$ = NASP Bond Test value (kips)

Three rectangular beams stressed with strand D had a bond failure at a 58 in. embedment length and three I-beams failed in bond with embedment lengths of 72 and 88 in. No beams stressed with strands A, B, or AA, which had a NASP Value of 15.0 kips, had a bond failure. Strand II had the lowest NASP Value (4.1 kips) and had bond failures at a 73 in. embedment length. Strand HH had a NASP Value of 10.7 kips. All four tests with strand HH and a 73 in. embedment length were flexural failures. However, one of the four tests with a 58 in. embedment length (80 percent of the development length) was a bond failure. Using the results of these development length tests, Ramirez and Russell recommended minimum values for the NASP Tests. Because strand HH had no bond failures when tested at the development and did have a bond failure at 80 percent of the development length, the bond quality of this strand was near the limit to fully develop the strand in the AASHTO LRFD calculated development length. Therefore, the authors chose a minimum average NASP Bond Test Value of 10.5 kips for 0.5 in.

diameter strand with no individual test below 9.0 kips. A summary of the strand types, average NASP Values and flexural test results for this research by Ramirez and Russell (2007) is shown in Table 2.3.

Table 2.3 NASP Values and Bond Failures from Ramirez and Russell

Strand	Average NASP Value (kips)	Number of Bond Failures	
		58 in. Embedment Length	73 in. Embedment Length
A	21.0	0	0
B	20.2	0	0
AA	15.0	0	0
HH	10.7	1	0
D	6.6	3	2
II	4.1	4	2

Development length tests were performed on 0.6 in. diameter strand from one manufacturer. Strand A6 had an average NASP Value of 18.3 kips. None of the 16 beam tests with an embedment length of 70 in. or more had a bond failure. Three of the five tests with a 58 in. embedment length were bond failures; however, this is much shorter than the AASHTO LRFD development length of 88 in. The authors recommend thresholds of 12.6 kips for the average NASP Value, and 10.8 kips for an individual test for 0.6 in. diameter strand. These numbers are the limits for 0.5 in. diameter strand multiplied by the ratio of the strand diameters.

2.4 Large Block Pullout Test

2.4.1 Rose and Russell

The researchers in this study (Rose and Russell 1997) performed three different pull-out tests and compared the results with measured transfer lengths in order to investigate the tests' ability to evaluate strand bond quality. The tests consisted of measured end slip, a pull-out test of untensioned strand, and a tensioned pull-out test. The main variable was strand surface condition. Strands from three manufacturers were tested. Strands from two of the producers were tested only in the as-received condition. Strands from the third producer were tested as-received, cleaned with muriatic acid, weathered after being cleaned, and coated with silane after being cleaned. The weathered strands were cleaned with muriatic acid and left in an environmental chamber with 75 percent humidity where they were misted with water 3 times a day. The silane was used to slightly lubricate the strand surface. Twelve simple pull-out tests, two tensioned pull-out tests, and three transfer length beams were cast for most surface conditions. Because longer beams were required, only two transfer length beams were cast for the silane treated strand. The transfer length beams measured 6 in. by 12 in. and were 17 ft long for all but the silane treated strand, which had beam lengths of 24 ft. The simple pull-out test blocks were 2 ft by 3 ft by 4 ft with strands on a 4 by 3, 9 in. grid spacing. Each strand went all the way through the block with a 4 in. bond breaker at the bottom and a 2 in. bond breaker at the top, which gives an 18 in. embedment length. These blocks are similar to the Large Block Pullout Test used in association with this thesis. The tensioned specimens were 12 in. long and had a 5.5 in. square cross section. They were cast against a stiffened plate in the center of the frame used to tension the strands. All specimens were cast with a concrete mix that had a target release strength of 4000 psi.

Transfer lengths were determined by measuring concrete surface strains with mechanical strain gauge points spaced at 3.94 in. and a strain gauge with a 7.87 in. gauge length. The 95 percent Average Maximum Strain method was used to determine the transfer lengths from the measured concrete strains. Readings were taken immediately before and after release of prestress, which was done by flame cutting the strands. End slips were also measured on the transfer length specimens. These measurements were taken by attaching a metal clamp on each strand and measuring the change in distance from the end of the beam. During the simple pull-out tests, slip was monitored at the free end and the jacking end using aluminum clamps and linear potentiometers. The strand was loaded until the free end slipped 1 in., and loading was stopped to record data at regular intervals of free end slip. The pauses in loading resulted in a relatively slow load rate and each test took about 15 to 20 minutes. The tensioned pull-out test was performed by releasing the tension on one side of the block with jacking bolts.

All of the as-received strands performed well in the transfer length tests. Strand from manufacturer A, B, and C had transfer lengths of 19.1, 15.7, and 14.4 in., respectively. The transfer length of the cleaned strand from manufacturer C measured 15.4 in. and, the weathered C strand had a 12.5 in. transfer length. The silane treated strand did not perform well in the transfer length tests. The average transfer length was 65.8 in., and the data indicated that the strand could not fully transfer the pretension to the concrete. In the pull-out tests, as-received strand from manufacturer B and C had similar pull-out strengths. However, the as-received strand from producer A had pull-out strengths of about half that of B and C. The cleaned strand from producer C had a slightly higher pull-out strength than the as-received strand. The weathered strand performed the best of all of the strand samples in the simple pull-out test. The silane treated strand slipped at lower forces than most of the other stands but saw a significant increase in load after its first slip. Its maximum loads exceeded the as-received strand from manufacturers A and B. The weathered strand reached its maximum load shortly after it first slipped and had only a slight increase in load after the slip. The other strands all had a significant increase in load after slip but not to the extent of the silane treated strand. When the authors compared the pull-out forces to the transfer lengths, omitting the results from the silane treated strand, the data showed a strong correlation. The correlation value for the linear regression analysis was 0.945. The author points out that while the regression analysis shows a definite relationship between transfer length and pull-out strength, the equation developed does not indicate a good physical relationship between the two. For example, a pull-out strength of zero would give a transfer length of 23 in. The data showed that a large change in pull-out strength resulted in a relatively small change in transfer length. On the other hand, if the results include the data for the silane coated strands then there is little to no correlation between pull-out forces and transfer lengths (Rose and Russell 1997).

2.4.2 Logan

The purpose of this study by Logan (1997) was to compare the bond quality of strand from different manufacturers and to correlate the results of Large Block Pullout Tests to transfer and development length tests. The design and procedure of the pullout tests were the guidelines used in the LBPT's performed as part of this thesis. The author also wanted to determine a minimum acceptable pull-out strength and to determine if there are any obvious surface features that can indicate bond quality. The researcher collected grade 270, 0.5 in. regular strand from five different strand producers. Strand from one producer was divided into two sets, the first of which was kept in the as-received condition and the second was exposed to the weather and allowed to develop a coat of rust. These two samples were labeled TA and TW. The other four samples were labeled A, B, D, and ER. Each strand type was examined to determine surface condition and was wiped with a cloth to examine the residue on the strand. The pull-out tests consisted of 34 in. pieces of untensioned strand cast into two 24 in. wide blocks. The strands were placed in two rows along the length of the blocks with 12 in. between rows and 8 in. between the strands along each row. Each strand was embedded 20 in. into the block with a 2 in. bond breaker at the concrete surface to reduce the effects of concrete spalling. Six pieces of each type of strand were tested. The design used for the Large Block Pullout Tests in this project is based on Logan's recommendations above.

The beam specimens were 6.5 in. by 12 in. by 90 ft and were pretensioned with a single 0.5 in. diameter strand 2 in. from the bottom of the cross section. One 90 ft beam was cast for each strand type. The beams were subjected to a sudden strand release and were then cut into five 18 ft pieces. The beams and blocks were cast with a concrete mix designed to achieve a 4000 psi compressive strength at prestress release and a 28-day compressive strength of 6000 psi.

The pull-out tests were performed with a hollow ram and a small steel frame. The strands were pulled out at a load rate of 20 kips per minute. The load at first slip, maximum load, slip at failure, and failure characteristics were recorded for each test. Groups A, B, TA, and TW exhibited good bond quality and had average pull-out strengths of 37.7, 36.8, 40.0, and 41.6 kips, respectively. All but one of the 24 pull-out tests on these four strand groups had sudden failures after 0.5 to 2 in. of slip. Groups D and ER had maximum average pull-out strengths of only 11.2 and 10.7 kips, respectively. These tests did not have an abrupt failure and did not reach their maximum loads until 6 to 8 in. of slip.

The transfer lengths were calculated using end slip measurements. End slip was measured immediately after release and 7, 14, and 21 days after release. Logan used the following equation to calculate transfer lengths from the measured end slips, which assumes a linear variation in strand stress over the transfer length:

$$L_t = \frac{\Delta E_{ps}}{0.5 f_{si}} \qquad 2\text{-}5$$

Where:

L_t = transfer length (in.)

Δ = measured end slip (in.)

E_{ps} = elastic modulus of prestressing strand (ksi)

f_{si} = average initial prestress (ksi)

Five of the strand groups had an initial transfer length less than the 29 in. predicted by ACI 318. Strand groups A, B, TA and TW had average initial transfer lengths less than 15 in. and group D had a transfer length of 24 in. Group ER, on the other hand, had an average initial transfer length of 34 in. and had one transfer length of 53 in. After 21 days the average transfer lengths of group D and ER increased by 16 and 12 in., respectively. The other groups only showed a small increase in transfer length after release.

The development length tests consisted of four load configurations. Each setup had two timber supports. Two tests were done as simple beams and two were cantilever beams. The cantilever tests were restrained at the far support and were unrestrained at the support nearest the load. The two cantilever setups were loaded with overhangs of the calculated development length (6.08 ft) and the calculated transfer length (2.42 ft), and the two simple span configurations were loaded at the 6.08 ft development length and at 4.83 ft, or 80 percent of the development length. Strand groups A, B, TA, and TW had flexural failures in both tests with a 6.08 ft embedment length and in the test with a 4.83 ft. embedment length. Of these four groups only sample TW did not have a flexural failure in the cantilever test with a 29 in. embedment length. Strand TW did, however, develop a strand stress higher than that of strand A, which failed in flexure. Strand groups D and ER performed poorly in all of the beam tests. All of the tests resulted in a bond failure, and most of the failures occurred after only one crack had formed under the load. Because the four strands with pullout capacities of 36.8 kips or more had transfer and development length longer than those calculated from ACI 318, the author recommended a minimum pullout capacity of 36 kips. Logan also states that strands that exceeded this capacity far exceeded the required performance and that strands with a lower pullout strength would probably meet the transfer and development length requirements. However, no testing was done on strands with pullout capacities between 36.8 and 10.1 kips, so the limit could not be lowered. No threshold values were given for 0.6 in. diameter strand (Logan 1997).

2.4.3 Brearley and Johnston

The researchers in this study (Brearley and Johnston 1990) performed pull-out tests on epoxy-coated and uncoated grade 270 low-relaxation strand of three different sizes with varying amounts grit impregnated in the epoxy. The specimens used were 12 in. long and had an 8 in. square cross section. The strands went all the way through the prisms in the center of the cross section. Of the 52 specimens cast, 20 were uncoated strand with five 3/8 in. strand specimens, eight 1/2 in. diameter strands and seven 0.6 in diameter strands. The strand used in this study is the same strand used by Cousins (1986). The specimens were cast along with the beams used by Cousins and were subjected to the same curing method. The target compressive strength for the mix was 4000 psi after 4 to 7 days and 5000 psi after 28 days.

The strands were pulled out of the specimens using a hollow hydraulic ram and a manual pump. Slip was monitored at the free end and the loaded end with dial gauges. Load was applied in 500 or 1000 lb increments until the strand slipped at the free end. The strand was then loaded to maximum load. Loading was stopped at each increment and slip was recorded after the bond creep had stopped. The bond stress was calculated as the force divided by the circumference of the strand multiplied by the length of the prism. The force used to calculate the plastic bond stress, U_p, was the force at first slip and the maximum bond stress, U_m, used the maximum force. The stresses were divided by the square root of the compressive strength of the concrete so a more uniform comparison of the specimens could be made. The resulting values are labeled U_p' and U_m' and are referred to as bond stress coefficients. For 1/2 in. diameter uncoated strand, the average plastic bond stress is 285 psi and the average maximum bond stress is 295 psi. In six of the eight tests the plastic bond stress and the maximum bond stress were the same value. The average plastic bond stress coefficient is 3.67, and the average maximum bond stress coefficient is 3.81. The plastic and maximum bond stress coefficients were compared to the bond coefficients in the transfer and flexural bond length. The author states that the bond in the prism specimens is similar to that in the flexural bond length except that the forces in the strand are smaller. The smaller load will result in less friction reduction between the concrete and steel due to Poisson's effect. Therefore, the bond stress in the prism should be higher than that in the flexural bond length. The bond stress in the transfer length, however, should be higher than the stress in the prism because the wedging at the end of the strand due to Poisson's effect will increase the friction between the concrete and steel in the transfer length of a beam. The plastic and maximum bond stress coefficients for 1/2 in. diameter uncoated strand did lie between the bond stress coefficients in the transfer and flexural bond lengths of 1.32 and 6.70 as predicted. Finally, the author concludes that while the test results do show the same pattern as the bond quality in the beams, the test is not an accurate predictor of the actual bond stresses (Brearley and Johnston 1990).

2.4.4 Mote

As mentioned previously in this literature review Mote (2001) performed four different bond tests on prestressing strand. One of these tests was the Moustafa Pullout Test, or as it is known today the Large Block Pullout Test. The test specimen design and testing procedure is similar to the design and procedure of the LBPT's used in this thesis because both tests are based upon the guidelines provided by Logan (1997).

The specimens used by Mote measured 24 in. wide and 24 in. deep. The block was 80 in. long with strands spaced 12 in. apart every 8 in. along the length of the block. The strands extended 20 in. into the concrete with a 2 in. bond breaker at the top resulting in an 18 in. embedment length. The concrete mix used had a target strength of 3500 to 5900 psi. A hydraulic ram was used to load the strand. The ram's cylinder was extended and a yoke was attached to the cylinder. The strand was anchored to the yoke with a prestressing chuck. The strands were then loaded at 20 kips/minute to failure. A summary of the results from the Moustafa Pullout Tests by Mote can be seen above in Table 2.2. The Moustafa tests corresponded well with the other three types of pullout tests performed. A definite difference in the bond quality between manufacturers could be noted from the results of the Moustafa tests (Mote 2001).

2.5 Summary

Much research has been done on the material properties of grade 270 prestressing strand, but almost no research exists for grade 300 strand. This thesis provides some data on the material properties of grade 300 prestressing strand through the results of tensile tests. A common problem in tensile tests of prestressing strand is notching and subsequent premature failure of strands. Research by Hill (2006) has shown that a method similar to the aluminum insert method in ASTM A370 (2005) is an effective way to cushion the strand and reduce the risk of strand rupture in the grips.

Transfer and development lengths in strands can vary widely. One of the major factors in predicting transfer and development lengths is strand surface condition. Multiple tests have been developed to quantify the surface condition of prestressing strand. Two such tests are the Large Block Pullout Test (LBPT) and the North American Strand Producers (NASP) Bond Test. The results of both tests have shown a strong correlation to transfer and development lengths. Few pullout, transfer length, or development length tetss have been done to assess the bond properties of grade 300 strand. Using the LBPT and the NASP Test, the bond quality of Grade 270 and grade 300 strand was investigated in this thesis. In addition, the results of the pullout tests were compared to transfer and development lengths measured from beam specimens using the same strand as that used for the pullout tests, further adding to the database of information on the ability of the NASP Test and LBPT to assess bond quality.

3. TEST SPECIFICATIONS, INSTRUMENTATION, AND PROCEDURE

3.1 Introduction

This chapter provides details about the testing program used for this thesis. Three different tests were performed: strand tensile tests, the North American Strand Producers (NASP) Bond Test, and the Large Block Pullout Test (LBPT). All specimens were cast and tested at the Virginia Tech Structures and Materials Laboratory. Three different size strands were used. The 0.5 in. diameter regular strand has a cross sectional area of 0.153 in.^{2} and the 0.5 in. diameter super strand has a cross sectional area of 0.167 in.^{2} The largest strand tested was the 0.6 in. diameter strand, which has a cross sectional area of 0.217 in.^{2} All strands used had some small rust spots on the surface but were mostly in bright condition as shown in Figure 3.1. The strands for each specimen were cut with a circle grinder.

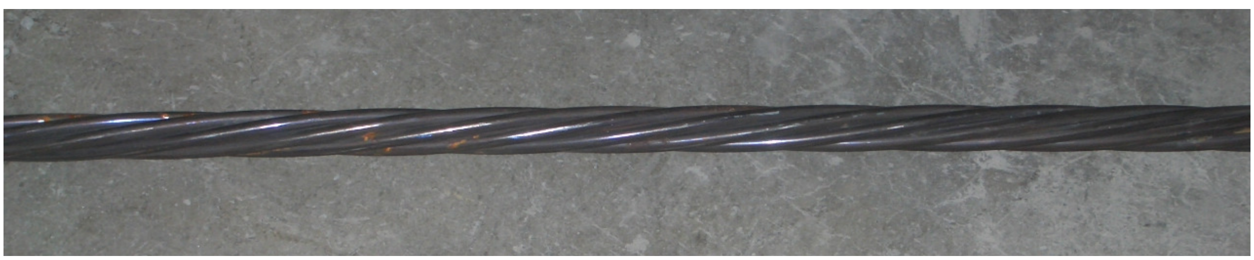

Figure 3.1 Typical Surface Condition of Prestressing Strand

3.2 Nomenclature

Each individual test was given a unique name. The naming method can be seen in Figure 3.2**.** The first term designates the type of specimen. The size and grade of the strands are denoted by the second and third terms, respectively. The fourth term indicates which manufacturer produced the strand and for the case of the grade 270 super strand, which reel the strand came from. The final term is used to distinguish between different tests with the same parameters.

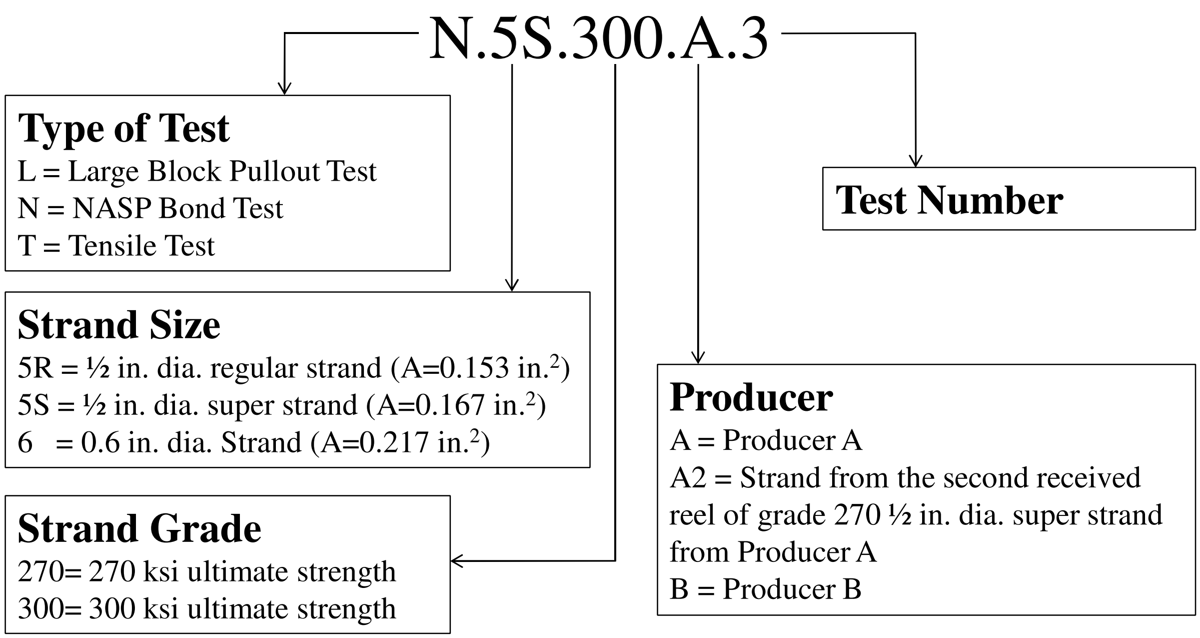

Figure 3.2 Test Specimen Nomenclature

3.3 Tension Tests

The tension tests were performed on seven different strand types. The combination of strand sizes, grades, and manufacturers are shown in Table 3.1. The tests were performed in order to determine the modulus of elasticity, yield stress, ultimate stress, and ultimate strain for each type of strand. All strand tested was low-relaxation strand. The main guidelines used for testing were those given by ASTM A370 (2005), ASTM A416 (2005), and Hill (2006).

Table 3.1 Tension Test Matrix

Strand Diameter (in.)	Strand Area (in.^{2})	Strand Grade (ksi)	Manufacturer	Tests Performed
0.5	0.153	270	A	6
0.5	0.153	300	A	8
0.5	0.153	300	B	10
0.5	0.167	270	A	7
0.5	0.167	270	A2	6
0.5	0.167	300	A	6
0.6	0.217	270	A	6

3.3.1 Tension Test Setup

The strand was received from the manufacturer in rolls of about 80 ft. The strand was cut to lengths of 52 in. with a circle grinder shown in Figure 3.3. ASTM A370 states that high heat can damage a strand. While the grinder did heat the ends of the strand specimens, only a small length of the strand was heated. The damaged portion of the strand extended past the grips during testing and was not loaded.

Figure 3.3 Circle grinder used to cut strands

In order to prevent premature failures when testing the prestressing strand, aluminum tubing was used to cushion the strand in the grips. The gripping method used is similar to that used by Hill (2006). The tubing had a 3/4 in. diameter and wall thickness of 1/16 in. The tubing was cut in half along the length and then cut into 8 in. sections with a vertical bandsaw. A mix of 80 grit aluminum oxide, epoxy resin, and fast hardener were used to attach the strand. The ingredients are shown in Figure 3.4.

Figure 3.4 Epoxy resin, hardener, and aluminum oxide grit used to attach tubing to strand

Approximately 5 fl oz of aluminum oxide and 5 squirts each of epoxy resin and fast hardener was mixed in a container. This amount of epoxy is enough to prepare two or three strand specimens. The epoxy mix was then poured into the half sections of tubing; two sections were placed about 1 in. from each end of the strand. A plate was placed over the ends to compress the ends together and the epoxy cured overnight. The excess epoxy was cleaned off of the tubing after hardening so it would not fill in between the teeth in the grips. The grips' teeth embedded into the tubing during testing rather than into the strand itself. Therefore, notching was prevented and fewer premature breaks occurred. The aluminum tubing grips both before and after testing can be seen in Figure 3.5.

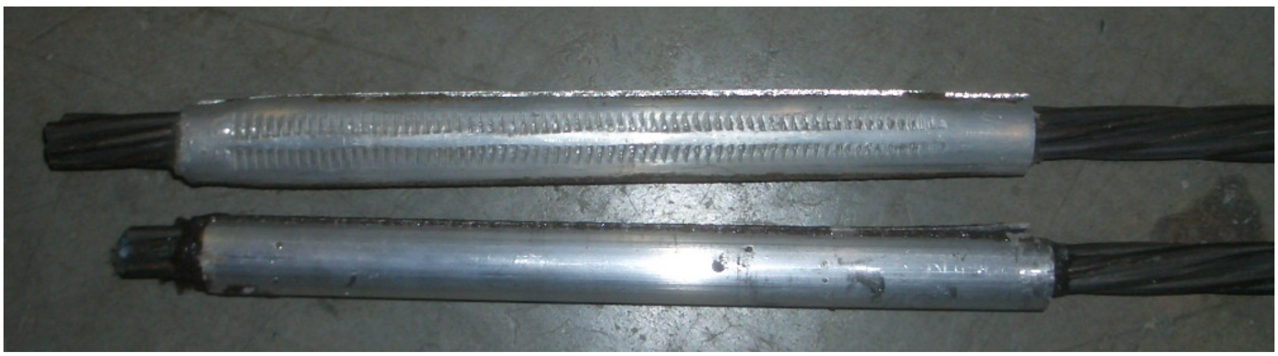

Figure 3.5 Aluminum Tubing Grips

The strand was tested in a SATEC universal testing machine. The strands were gripped with hydraulic wedge V-grips seen in Figure 3.6. The grips had a 4 in. grip length and 12 teeth per in. Because of the 52 in. strand lengths and two 8 in. grip lengths, each test had approximately 36 in. between the hydraulic heads on the machine.

Figure 3.6 V-Grips used in tension tests

3.3.2 Tension Test Instrumentation

The SATEC universal testing machine was controlled with a MTS 407 controller. The SATEC had three crossheads. The top and bottom crossheads were moved with the MTS 407 and the center crosshead was controlled with a lever. The top and center crossheads had hydraulically controlled wedge grips used to hold the strand during testing. During a test, the center crosshead remained stationary and the top crosshead moved up, tensioning the strand. The data from the crosshead displacement, extensometer, and load were exported to the data collection system from the MTS controller, shown below in Figure 3.7. Load, crosshead displacement, extensometer displacement, and time were recorded during each test.

Figure 3.7 MTS 407 Controller

ASTM recommends a 2 in. and 24 in. extensometer be used during testing. However, only a 2 in. extensometer was available. The extensometer used was a SE 2-50 Extensometer with a 2 in. gauge length and is shown in Figure 3.8. The extensometer output was provided as displacement (in.) and was converted to strain in the data analysis. The extensometer was calibrated to the nearest 0.0001 in. and was checked numerous times during testing. The extensometer was attached at mid-length of the specimen. Two-sided foam tape and rubber bands were used to hold the extensometer in place on the strand as shown in Figure 3.8.

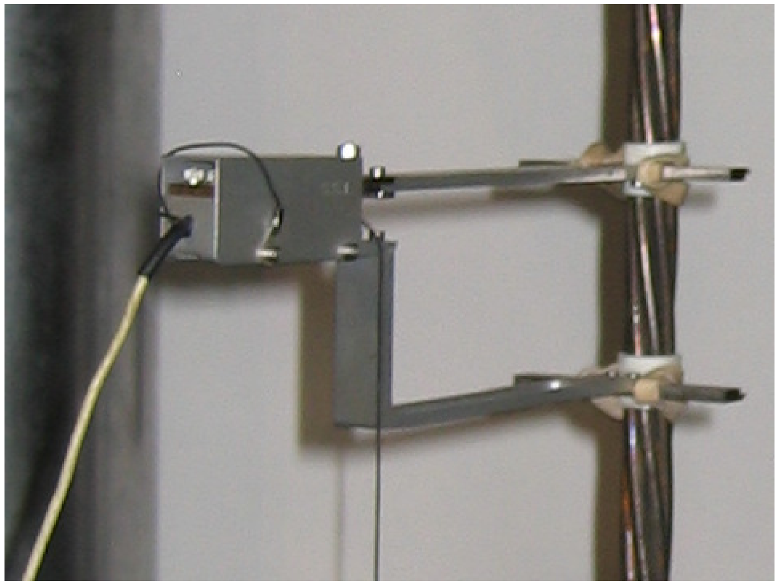

Figure 3.8 Extensometer used in tension tests

3.3.3 Tension Test Procedure

After the tubing was attached to the strand and excess epoxy removed, the specimens were placed in the hydraulic grips. It is important to ensure that the strand is vertical in the grips as any deviation can result in bending stresses, which could cause a premature failure at the grips. The load cell was zeroed and a small amount of tension (about 1 kip) was then applied to the strand to seat the grips and to straighten the strand. The tape and extensometer were then attached ensuring that the extensometer was straight and that the knife edges of the extensometer were 2 in. apart.

ASTM A370 states that strand should be subjected to a load rate between 10 ksi/min and 100 ksi/min. However, the tests were displacement controlled so that the strands would not be subjected to a high strain rate after yielding. The displacement rate used in preliminary testing was set to 0.05 in./min, which would result in a load rate of 42 ksi/min for a test with a 34 in. gauge length if there was no slip at the grips. However, a significant amount of slip occurred at the interface between the epoxy and the aluminum tubing. Therefore, the displacement rate was increased to 0.075 in/min, which resulted in a load rate of about 20 ksi/min for most tests.

The strand was loaded until the tensile strain reached about 1.2 percent at which time the extensometer was removed so that it would not be damaged due to strand rupture. After the extensometer was removed the displacement rate was doubled to reduce testing durations. The strand was then loaded to failure. After rupture, the tension in the strand was released if a clear break—a break away from the grips—did not occur. Finally, the strand was removed from the grips and all collected data was saved and reduced into Excel spreadsheets. An example of a test with a clear break and an example of a test with a break in the grips are shown in Figure 3.9.

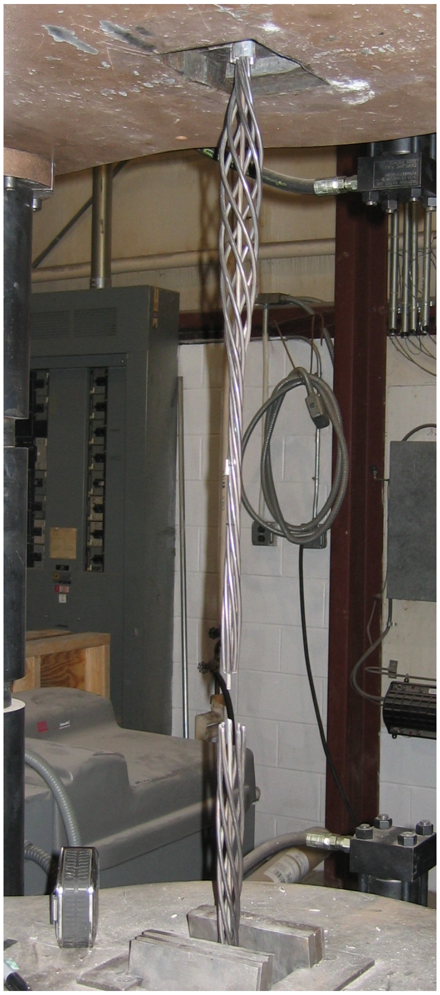 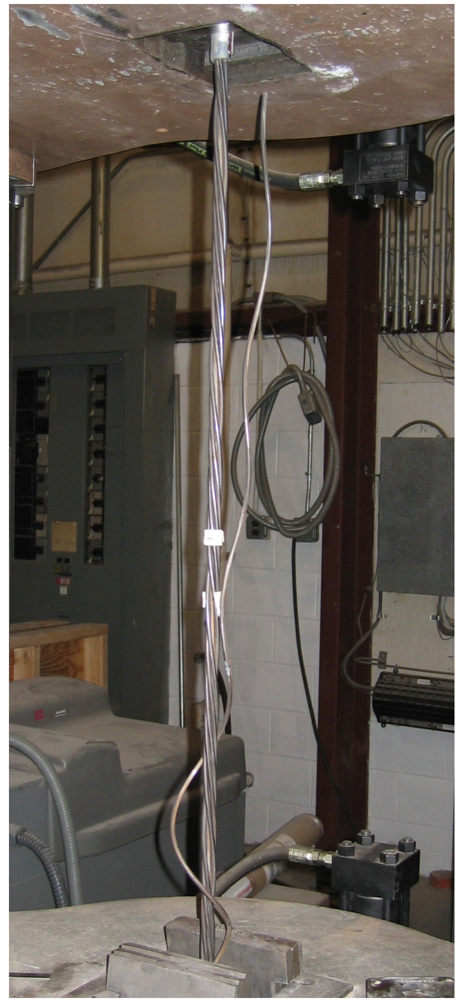

Figure 3.9 Left: Clear break in middle; Right: Single strand break in grips

3.4 NASP Tests

3.4.1 NASP Test Specimen Design

The NASP Bond Test specimens consisted of an 18 in. long, 5 in. diameter steel tube and a 1/2 in. thick, 6 in. by 6 in. plate. The plate was welded to one end of the tube to seal the tube for concrete placement and to provide a flat surface to accommodate testing. A 9/16 in. hole was punched in the plate for tests of 0.5 in. diameter strands and an 11/16 in. hole was used for tests of 0.6 in. diameter strand. A small piece of angle was welded to the end of the tube opposite the plate in order to provide a surface to which a linear variable differential transformer could be attached. A typical specimen can be seen below in Figure 3.10.

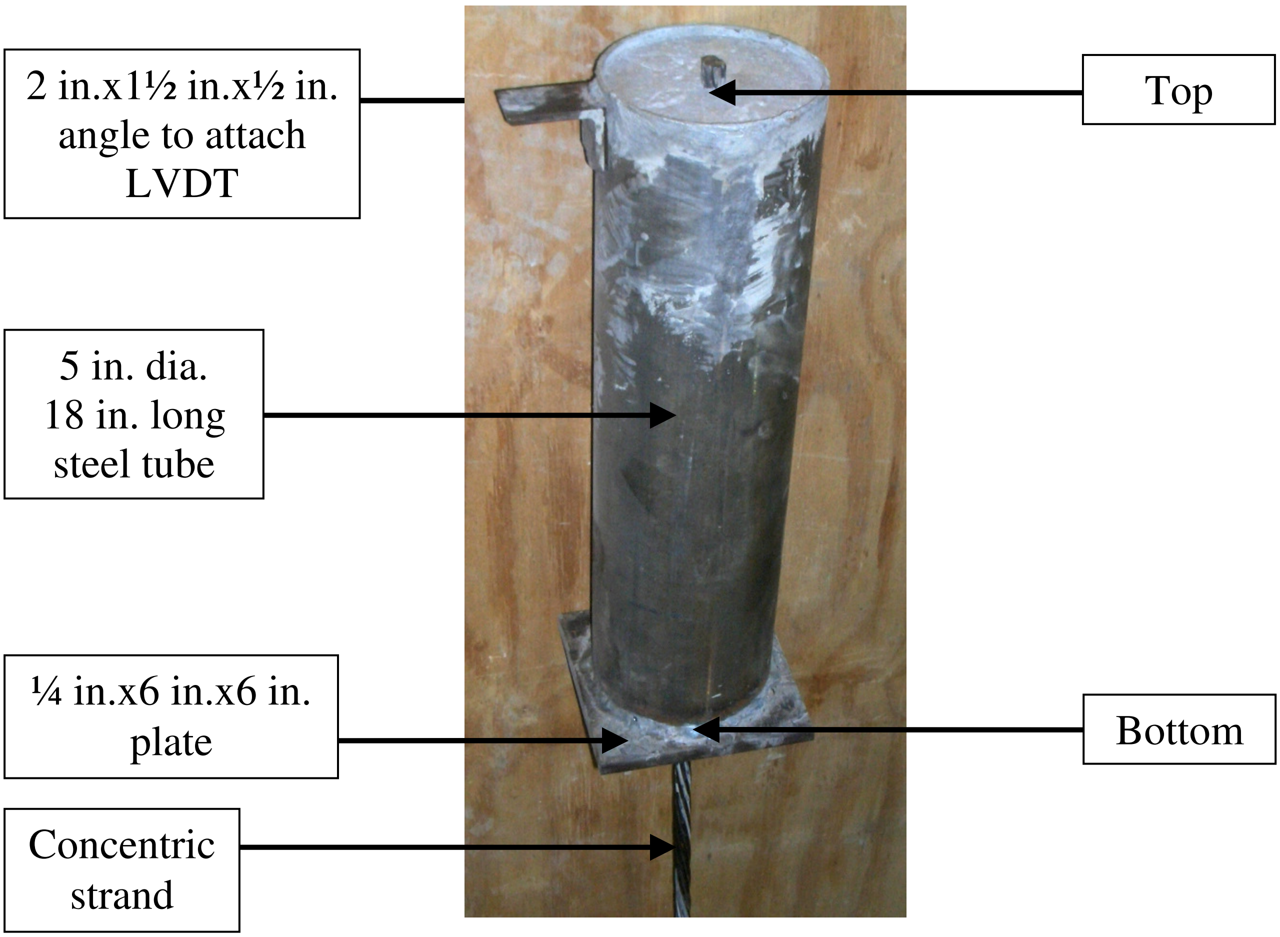

Figure 3.10 Typical NASP Test

The most challenging aspect of the NASP Bond Test was developing a mortar mix which would satisfy the provided flow and strength requirements. The measured flow was required to be between 100 and 125 and the strength at 24 hours was required to be between 4500 psi and 5000 psi. The mortar mix consisted of Type III cement, sand, and water. Over 50 trial batches were mixed in order to develop a mix that consistently met the requirements. A shortage of materials contributed to the need for so many trial batches. The cement manufacturer and the sand used in testing were changed during testing, both of which greatly affected the mix properties. The initial cement and sand are cement A and sand A, while the others are cement B and sand B. The required strength could not be obtained with the second batch of sand. Therefore, the sand particles passing a No. 50 sieve were taken out of the sand. Removing the fine particles from the sand increased the flow, which allowed the use of a lower water-cement ratio thus increasing the strength of the mix. The mix proportions used for each test are shown in Table 3.2. Tests N.5R.270.A contained sand and cement A while the other five mixes used sand and cement B.

Table 3.2 NASP Test Mix Proportions

Test	Oven-Dried Sand (lb.)	Type III Cement (lb.)	Water (lb.)	Sand Type	Cement Type
N.5R.270.A	100	72	31.6	A	A
N.5S.270.A	100	80	32.8	B	B
N.5S.270.A2	100	72	31.6	B	B
N.5S.300.A	100	80	32.8	B	B
N.6.270.A	100	80	32.8	B	B

3.4.2 NASP Test Specimen Fabrication

The strands to be tested were cut to lengths of 38 in. A 2 in. duct tape bond breaker was placed on the strand so that the bottom of the bond breaker was at the bottom of the can. The bond breaker reduces the effects of confinement on the strand bond. The strands were then placed vertically in the cans. The strands project about 2 in. from the top of the can.

The mortar was mixed in a two cubic foot electric mixer. The oven-dried sand was placed in the mixer first and part of the water was added. Then the cement and the rest of the water were added. The mortar was mixed for approximately 3 minutes, the sides were scraped, and the mortar was mixed again for approximately 3 minutes. It was placed in the specimens in three lifts and was consolidated by rodding and tapping the sides of the specimen with a rubber mallet. The specimens were cured in an environmentally controlled room with a temperature of about 70 degree F. Wet burlap was placed on top of the specimens to keep them moist while curing.

3.4.3 NASP Test Setup

The NASP Test specimens were tested in the SATEC universal testing machine. The NASP Test protocols recommend that the strand be tensioned a distance of about 6 in. from the bottom of the specimen. In order to satisfy this provision, a steel frame, shown in Figure 3.11 and Figure 3.13, was used to tension the strand. The frame was designed using the breaking strength of a 0.6 in. diameter grade 300 prestressing strand which is around 65 kips. The frame consisted of four different ASTM A36 plates fillet welded together as seen in Figure 3.11. The bottom plate bore on the center crosshead of the SATEC. The can specimen sat on a 1 in. plate which rested on the top crosshead. The strand passed through an 11/16 in. hole in the top plate of the frame. The strand was gripped using a prestressing chuck such as the one shown in Figure 3.12**.** The chuck bore against the top plate in the frame. During the test the center crosshead and frame remain stationary while the top crosshead and test specimen move upward, thus loading the strand. A schematic of the test setup is shown in Figure 3.14.

The NASP Test calls for a displacement rate of 0.1 in./min. However, it also recommends that the load rate not exceed 8000 lb/min. As a result of this maximum loading rate, the specimens were tested at a load rate of 7500 lbs/min. The SATEC was controlled by an MTS 407 controller, which ensured the load rate remained constant.

Figure 3.11 Steel frame used in NASP Test

Figure 3.12 Prestressing Chuck

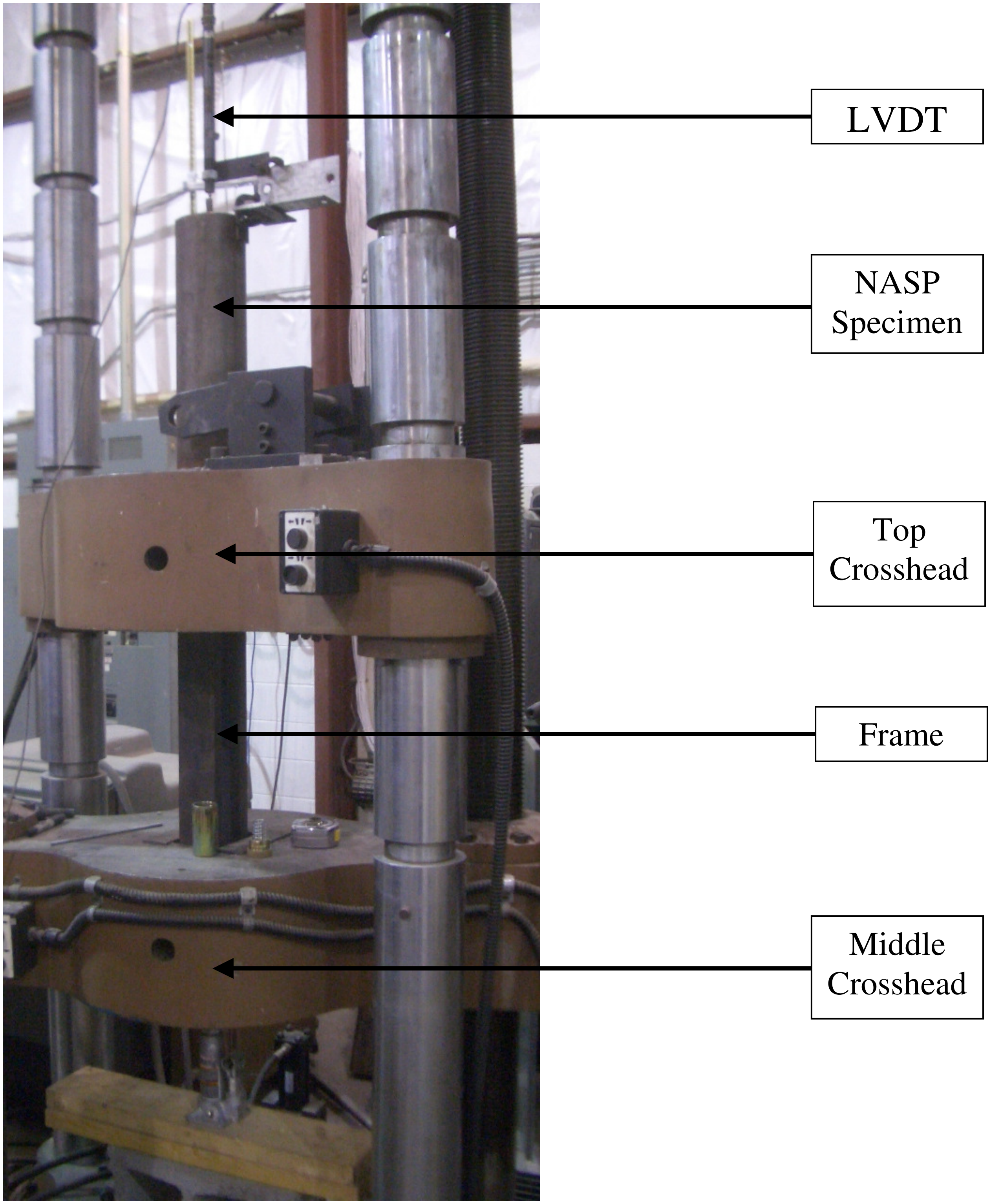

Figure 3.13 Typical NASP Test Setup

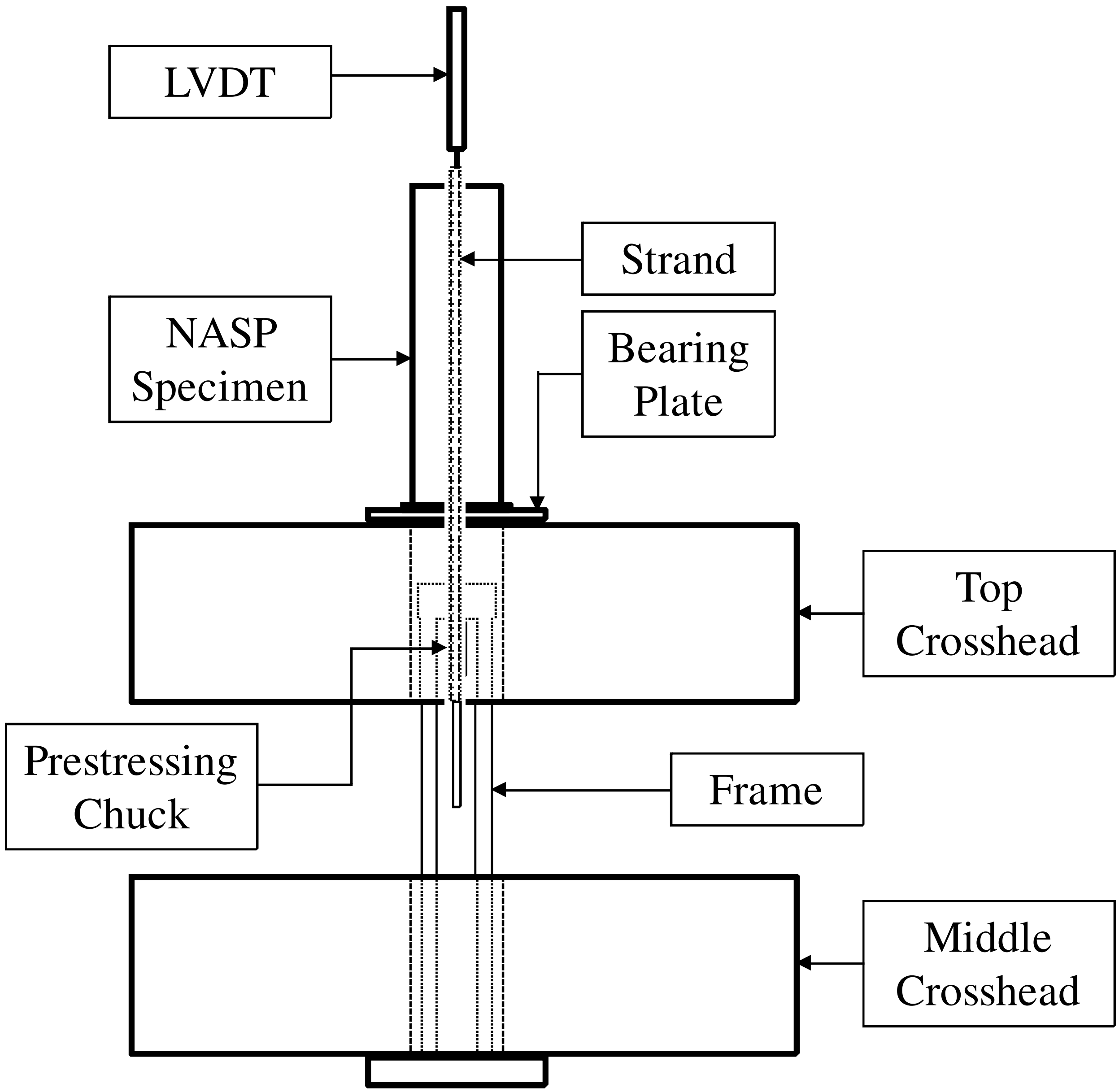

Figure 3.14 NASP Test Setup

3.4.4 NASP Test Instrumentation

Load, crosshead displacement, and free end strand slip were monitored during each test. The data was collected with a Vishay Instruments System 5000 and was processed with StrainSmart software package. Load and displacement were both output from the MTS 407 controller. The free end slip was monitored using a barrel linear variable differential transformer

(LVDT), which can be seen in Figure 3.13. The LVDT was suspended over the strand and secured to the can using clamps and angles. The LVDT had a 2 in. range and was calibrated to the nearest 0.001 in. Data was recorded twice per second.

3.4.5 NASP Test Procedure

After a 24 hour moist cure, the specimens were removed from the environmental chamber and the top ends of the strand were leveled and smoothed with a circle grinder. A specimen was placed on the top crosshead and the strand was threaded through the hole in the frame. The load was zeroed, and the prestressing chuck was placed around the strand and against the bottom side of the plate on top of the frame. The LVDT was placed vertically over the top of the free end of the strand with the plunger depressed at least 1 in. A small amount of tension was then placed in the strand, and the crosshead and LVDT displacements were zeroed.

The data collection system was armed and the loading was begun at 7500 lb/min. The specimen was loaded until the load on the strand could no longer be increased or until the free end slip reached about 1.5 in. After the test was completed, tension in the strand was released and the prestressing chuck was removed. The specimen was then checked for mortar cracking and removed from the testing apparatus. Finally, the data was saved and reduced to Excel spreadsheets.

3.5 Large Block Pullout Tests

3.5.1 LBPT Specimen Design

The specimens were designed with the guidelines set forth by Logan (1997). The blocks were 24 in. cubes as seen below in Figure 3.15. The strands were cut to a length of 68 in. so that a sufficient length would be available for the test setup. Four strands were used in each block. The strands were spaced at 12 in. in one direction and 8 in. in the orthogonal direction. The strands were embedded into the concrete 20 in. and had a 2 in. duct tape bond breaker at the concrete surface. The blocks were reinforced with two No. 3 hoops measuring approximately 20 in. by 16 in. spaced at 12 in. on center and two No. 4 longitudinal bars at the top and bottom of the specimen approximately 2 in. from the concrete surface.

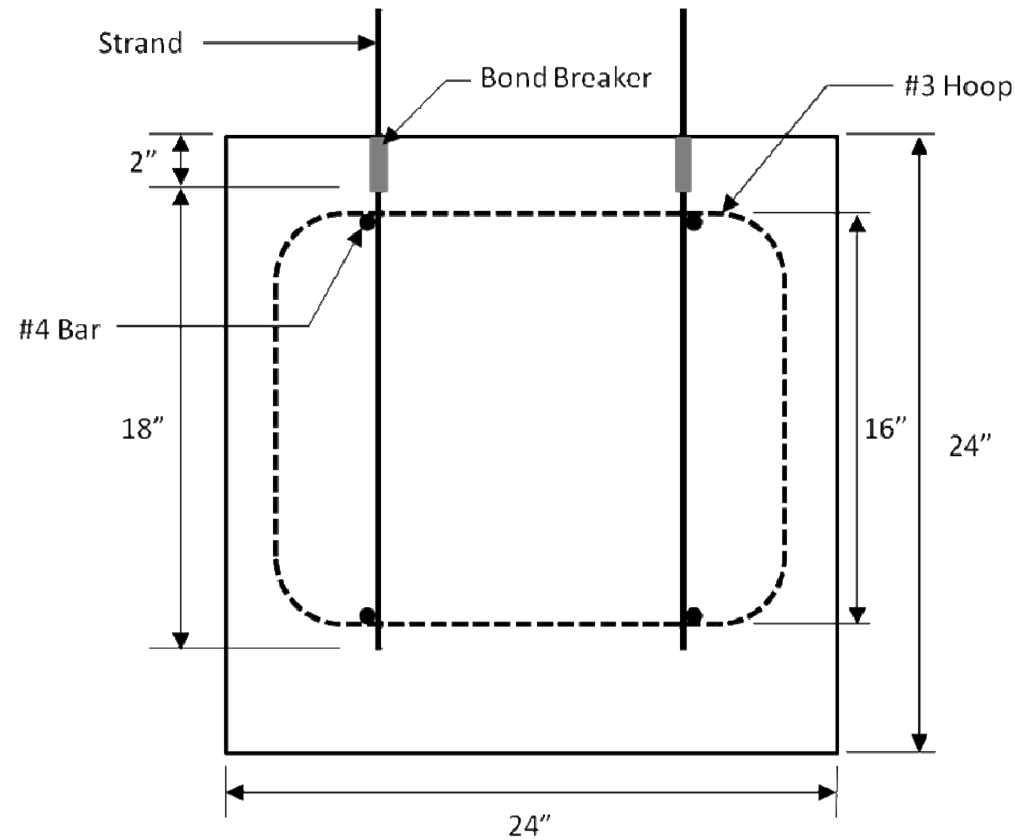

Figure 3.15 LBPT Specimen Design

3.5.2 LBPT Specimen Fabrication

The specimens were formed using formboard and 2x4's. Threaded rod was used to reinforce the formwork and to support the mild reinforcement during fabrication. The strands were tied to the longitudinal bars with rebar ties. The LBPT specimens and a few of the beams used in the transfer and development length testing were cast from the same batch of concrete. The mix had a target 28-day strength of 6000 psi. The mix proportions for the concrete are shown in Table 3.3. The concrete was consolidated using internal vibrators and finished with trowels to create a flat surface for testing. The specimens were covered with burlap and plastic and were moist cured for 7 days.

Table 3.3 LBPT Mix Proportions

Component	
No. 78 Stone	1443 lb
Sand	1083 lb
Type I Cement	600 lb
Fly Ash	150 lb
Water	36 gal
Super Plasticizer	19 oz
Retarder	19 oz
W/C Ratio	0.40

3.5.3 LBPT Setup

The Large Block Pullout Test was performed using an electric hydraulic pump and a hollow actuator. In order to better distribute the load to the concrete, a small steel frame similar to the one recommended by Logan (1997) was used. It consisted of four 3/8 in. by 2 1/2 in. by 2 1/2 in. angles welded to a 1 in. by 5 in. by 8 in. plate as seen in Figure 3.17. In addition, two steel plates and rubber pads were used under the frame to further distribute the load and to limit the effect of any roughness on the concrete surface. The actuator's piston rested on the top of the frame. A prestressing chuck was used to grip the strand and an aluminum spacer was used for ease of removal after the test. A typical test setup can be seen in Figure 3.16**.**

Figure 3.16 Typical LBPT Setup

Figure 3.17 Frame used in LBPT

3.5.4 LBPT Instrumentation

Load and strand slip were measured during each Large Block Pullout Test. The load was measured using a hollow cylindrical load cell. The load cell was placed between the ram and the prestressing chuck. The strand slip was measured with a linear variable differential transformer (LVDT). A small piece of angle was attached to the strand near the concrete surface with a hose clamp. A small piece of plate was then clamped to the angle. The barrel of the LVDT rested on the plate as seen in Figure 3.18. Data was recorded twice per second.

Figure 3.18 Frame and LVDT used in Large Block Pullout Test

3.5.5 LBPT Procedure

The specimens were tested within a few days of when the beams with which the blocks were cast were tested in flexure. First, the small piece of angle was clamped to the strand to measure slip, and the rubber pads and steel plates were placed on the concrete surface. The frame was threaded onto the strand and set on the plates. Using an overhead crane, the actuator was lowered onto the frame. Next, the load cell, spacer, and prestressing chuck were threaded onto the strand. The load cell was then zeroed and some tension was put on the strand to straighten it. Finally, the LVDT was put in place and the strand was loaded at approximately 20 kips/min. Due to safety concerns, some of the tests were stopped before a failure occurred because it was evident that the strand was near rupture. Nevertheless, two strands did rupture during testing.

The strand was loaded until the bond failed abruptly, the strand neared rupture, or the load in the strand began to decrease. After the test any tension left in the strand was released, and the collected data was saved and reduced to Excel spreadsheets.

4. RESULTS, ANALYSIS, AND DISCUSSION

4.1 Introduction

Grade 270 and grade 300 prestressing strands were tested to compare the material and bond properties of the two strand strengths. The strands were tested in tension to failure to determine the modulus of elasticity, yield stress, ultimate stress, and ultimate elongation and to develop a stress-strain curve. To compare the bond properties of the strands, two pullout tests were performed: the North American Strand Producers (NASP) Bond Test and the Large Block Pullout Tests (LBPT). The results of these tests were compared to transfer and development lengths measured from beam specimens made using strand from the same reels.

4.2 Tension Tests

Tension tests were performed on seven different types of strands for a total of 49 tests. The tests were performed in accordance with the procedure described in Section 3.3. This section presents the material properties derived from the tensile tests as well as discussion of these results. The cross sectional areas used in data analysis were 0.153, 0.167, and 0.217 in.^{2} for 0.5 in diameter regular strand, 0.5 in. diameter super strand, and 0.6 in. diameter strand, respectively.

4.2.1 Tension Test Results

The data from the tension tests was reduced to stress-strain curves from which the modulus of elasticity, yield stress, ultimate stress, and ultimate elongation were calculated. The stress-strain curve of test T.5R.300.A.1 is shown in Figure 4.1 as an example of a typical stress-strain curve. The stress-strain curves for all of the tension tests are shown in Appendix A. The strains were determined using the extensometer until it was taken off which occurred around 1.3 percent elongation. The rest of the strains were calculated using the recorded crosshead displacements.

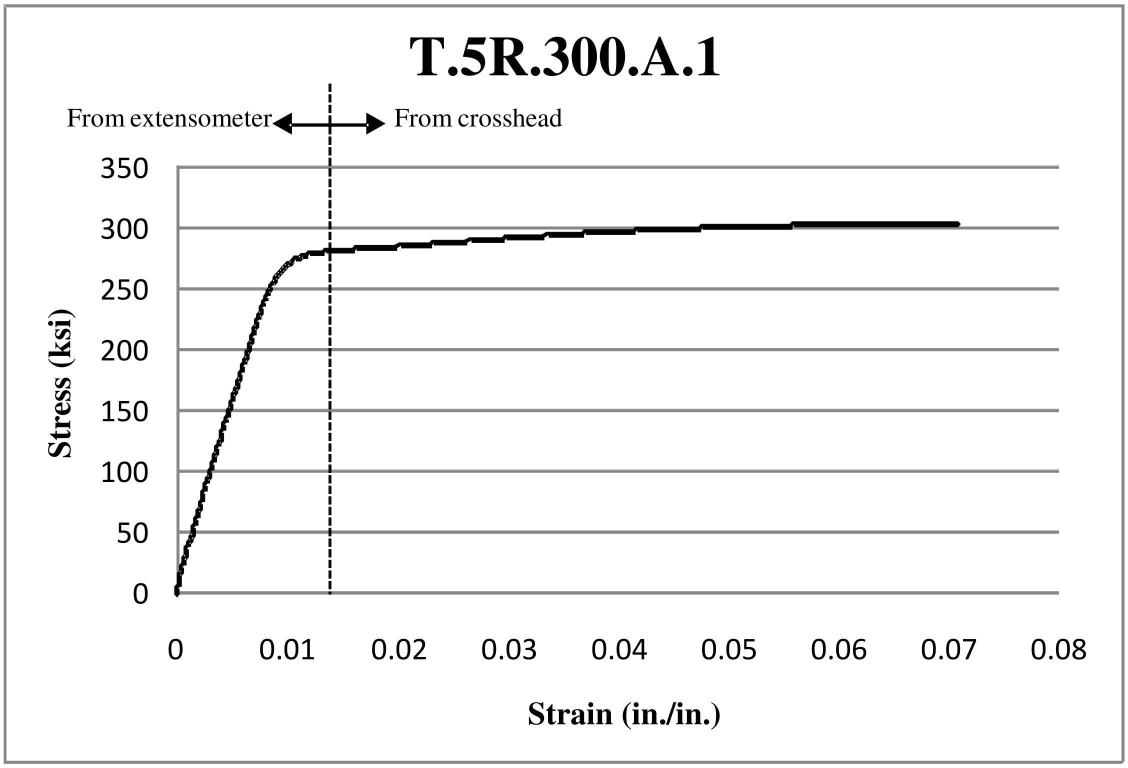

Figure 4.1 Stress-Strain Curve for T.5R.300.A.1

The modulus of elasticity, yield stress, ultimate stress, and ultimate elongation for each tested specimen can be seen in Table 4.1 through Table 4.5.

Table 4.1 Tension Test Results for Grade 270 0.5 in. Diameter Regular Strands

Test	Modulus (ksi)	Yield Stress (ksi)	Ultimate Stress (ksi)	Ultimate Elongation	Wires Broken
T.5R.270.A.1	31100	252	278	7.6%	7
T.5R.270.A.2	N/A	N/A	277	7.7%	7
T.5R.270.A.3	27400	246	279	8.0%	7
T.5R.270.A.4	30200	249	279	7.4%	7
T.5R.270.A.5	28900	245	279	7.1%	7
T.5R.270.A.6	28400	249	280	7.1%	7
Avg	**29200**	**248**	**279**	**7.5%**	
St. Dev.	**1460**	**2.44**	**0.99**	**0.35%**	

Table 4.2 Tension Test Results for Grade 300 0.5 in. Diameter Regular Strands

Test	Modulus (ksi)	Yield Stress (ksi)	Ultimate Stress (ksi)	Ultimate Elongation	Wires Broken
T.5R.300.A.1	29100	269	302	7.1%	7
T.5R.300.A.2	30400	271	304	7.3%	7
T.5R.300.A.3	30100	272	302	7.2%	7
T.5R.300.A.4	28800	263	303	7.9%	4
T.5R.300.A.5	29200	268	299	6.6%	6
T.5R.300.A.6	29600	267	299	7.4%	7
T.5R.300.A.7	32600	277	303	7.4%	7
T.5R.300.A.8	30400	272	300	6.0%	7
Avg	**30000**	**270**	**301**	**7.1%**	
St. Dev.	**1200**	**4.17**	**1.73**	**0.58%**	
T.5R.300.B.1	28000	277	298	8.2%	2
T.5R.300.B.2	29000	276	296	6.6%	7
T.5R.300.B.3	27700	272	297	6.5%	1
T.5R.300.B.4	28400	274	298	6.1%	1
T.5R.300.B.5	N/A	N/A	295	7.4%	1
T.5R.300.B.6	32600	280	293	5.6%	1
T.5R.300.B.7	N/A	N/A	293	7.2%	7
T.5R.300.B.8	34600	282	298	5.1%	1
T.5R.300.B.9	28400	266	294	5.3%	4
T.5R.300.B.10	28800	276	297	4.8%	3
Avg	**29700**	**275**	**296**	**6.3%**	
St. Dev.	**2510**	**4.82**	**1.89**	**1.10%**	

Table 4.3 Tension Test Results for Grade 270 0.5 in. Diameter Super Strands

Test	Modulus (ksi)	Yield Stress (ksi)	Ultimate Stress (ksi)	Ultimate Elongation	Wires Broken
T.5S.270.A.1	28700	236	264	6.6%	7
T.5S.270.A.2	28900	242	270	7.4%	3
T.5S.270.A.3	28800	239	267	7.2%	7
T.5S.270.A.4	27600	236	269	7.2%	1
T.5S.270.A.5	28100	238	265	7.1%	7
T.5S.270.A.6	29800	242	269	7.3%	7
T.5S.270.A.7	28600	238	267	7.3%	7
Avg	**28600**	**239**	**268**	**7.2%**	
St. Dev.	**685**	**2.50**	**2.30**	**0.26%**	
T.5S.270.A2.1	26200	231	268	7.3%	7
T.5S.270.A2.2	N/A	N/A	274	7.5%	7
T.5S.270.A2.3	28600	242	274	7.7%	7
T.5S.270.A2.4	26300	235	273	7.1%	7
T.5S.270.A2.5	N/A	N/A	272	7.1%	7
T.5S.270.A2.6	28400	235	275	7.6%	1
Avg	**27400**	**236**	**273**	**7.4%**	
St. Dev.	**1300**	**4.92**	**2.75**	**0.26%**	

Table 4.4 Tension Test Results for Grade 300 0.5 in. Diameter Super Strands

Test	Modulus (ksi)	Yield Stress (ksi)	Ultimate Stress (ksi)	Ultimate Elongation	Wires Broken
T.5S.300.A.1	28500	265	294	5.8%	1
T.5S.300.A.2	28500	268	294	5.2%	6
T.5S.300.A.3	28400	274	298	7.8%	1
T.5S.300.A.4	30000	274	298	9.7%	1
T.5S.300.A.5	28700	269	294	7.3%	7
T.5S.300.A.6	29000	274	298	7.4%	7
Avg	**28900**	**270**	**296**	**7.2%**	
St. Dev.	**602**	**4.03**	**2.26**	**1.59%**	

Table 4.5 Tension Test Results for Grade 270 0.6 in. Diameter Strands

Test	Modulus (ksi)	Yield Stress (ksi)	Ultimate Stress (ksi)	Ultimate Elongation	Wires Broken
T.6.270.A.1	30600	247	276	7.4%	7
T.6.270.A.2	27900	242	275	7.5%	7
T.6.270.A.3	28500	N/A	N/A	N/A	0
T.6.270.A.4	N/A	N/A	275	N/A	7
T.6.270.A.5	28900	N/A	N/A	N/A	0
T.6.270.A.6	26500	238	276	7.5%	7
Avg	**28500**	**242**	**276**	**7.5%**	
St. Dev.	**1490**	**4.23**	**0.47**	**0.06%**	

Some data is not available in the above tables because complications during some of the tests prevented the properties from being calculated. Because the extensometer slipped or crept during some of the tests, the elastic modulus, yield stress, and/or ultimate elongation could not be determined. The bond between the epoxy and the aluminum tubing failed in tests T.6.270.A.3 and T.6.270.A.5 and the strands could not be tested to failure. The adhesion at the interface did not fail until around 20 kips, or 90 ksi stress in the strand, and enough data was collected to determine the modulus of elasticity. For all tests shown above, if fewer than seven wires ruptured, the failure took place in the grips and if all seven wires ruptured, the failure took place between the grips.

4.2.2 Assessment of Aluminum Insert Gripping Method

The aluminum insert method used by Hill (2006) was an effective gripping method. However, some problems were encountered early in testing. In many of the initial tests, the strands were unable to be tested to failure because the bond between epoxy and the strand or the bond between the epoxy and aluminum tubing failed at low loads. The ratio of aluminum oxide to epoxy resin and fast hardener was changed several times before the mix described in Chapter 3 was proven to work best. Another problem encountered early in testing was breaks in the grips. However, in later tests much more care was taken to ensure that the strand was in the center of "V" in the grips and that the strand was straight in the grips. When these issues were resolved, strand broke all 7 wires between the grips around 85 percent of the time.

The strands tested with the aluminum tubing as cushioning material performed very well even when a clean break was not achieved. For many of the sets of tests the highest stress obtained was in a test that resulted in a failure in the grips. All of the tests had at least 3.5 percent additional elongation after yield. This performance indicates that although notching may occur during testing, the aluminum inserts provide enough cushioning that the notching does not occur until the strand has approached is breaking strength.

4.2.3 Modulus of Elasticity Analysis

The modulus of elasticity is the ratio of change in stress to change in strain in a material while the material obeys Hooke's Law. The modulus of elasticity for mild steel is typically taken as 29,000 ksi. Because the steel used in prestressing strand has a similar chemical composition to mild steel, one would expect a similar modulus of elasticity. Published recommended values are generally lower than 29,000 ksi but vary somewhat. The lower elastic modulus can be attributed to the helically wrapped wires straightening somewhat as the strand is tensioned. Nilson (1987) recommends an elastic modulus of 27,000 ksi, and the AASHTO LRFD Bridge Design Specification (2006) recommends a value of 28,500 ksi. Neither ASTM A416 (2005) nor ASTM A370 (2005) regulate the modulus of elasticity for prestressing strands.

Using the load from the MTS 407 and the displacement from the extensometer, the stress-strain curve for each test was plotted in Excel. The plotted data was then narrowed to the linear portion of the graph, which was generally in the stress range of 20 ksi to 200 ksi. A best fit line was determined through linear regression analysis, and the slope of this line was considered the modulus of elasticity for that strand. A summary of the results is shown below in Table 4.6.

Table 4.6 Summary of Modulus of Elasticity Results

Strand Type	Minimum (ksi)	Maximum (ksi)	Average (ksi)	Standard Deviation (ksi)
5R.270.A	27400	31100	29200	1460
5R.300.A	28800	32600	30000	1200
5R.300.B	27700	34600	29700	2510
5S.270.A	27600	29800	28600	685
5S.270.A2	26200	28600	27400	1300
5S.300.A	28400	30000	28900	602
6.270.A	26500	30600	28500	1490
Overall	26200	34600	29100	1590

Overall the modulus of elasticity results are near the expected values with an average modulus for all the tests of 29,100 ksi. The results of individual tests showed a large amount of variability with results ranging from 26,200 ksi to 34,600 ksi. However, the averages were reasonably close to expected values and ranged from 27,300 ksi to 30,000 ksi. Grade 300 0.5 in. diameter regular strand from producer B exhibited the most variable elastic modulus with measured moduli ranging from 27,700 ksi to 34,600 ksi and a standard deviation of 2510 ksi—almost twice that of any other strand. There appeared to be some effect from strand size on the modulus of elasticity. The smallest strands, 0.5 in. diameter regular strand, had the highest average modulus of 29,700 ksi and the largest strand size, 0.6 in. diameter strand, had the lowest average modulus of 28,500 ksi. The average modulus for 0.5 in. diameter super strands was 28,400 ksi. The modulus of elasticity was somewhat higher for grade 300 strand than for grade 270 strand. The average modulus for grade 300 strand was 29,600 ksi which is 3.8 percent higher than both the average for grade 270 strand and the modulus recommended by AASHTO of 28,500 ksi. While this difference is small, with sample sizes of 22 for grade 300 strands and 21 for grade 270 strands it is a statistically significant difference.

The main effect of modulus of elasticity in design is on prestress losses. A higher modulus of elasticity would results in greater prestress losses from creep and shrinkage of the concrete. As the concrete creeps and shrinks the strand will maintain its bond with the concrete and the strand will experience a compressive strain. The tension stress lost due to a given strain is proportional to the modulus of elasticity of the strand. The modulus of elasticity for many of the strands tested was higher than the recommended modulus from AASHTO LRFD of 28,500 ksi. Therefore, slightly higher losses may result than those predicted using this value. Another consequence of a higher modulus of elasticity is a lower elongation during prestressing. In a prestressing yard, elongation is measured as a check to ensure that strands are stressed to the proper level. If the elongation of the strand is less than expected it could result in overstressing of the strand.

4.2.4 Yield Stress Analysis

Unlike mild steel, prestressing steel does not have a definite yield plateau. From ASTM A370 (2005), the yield stress for prestressing strand is considered to be the stress in the strand at one percent extension past an initial pretension of 10 percent of the ultimate load. This method is accurate as the ratio of change in strain to change in stress is relatively low after about one percent elongation. ASTM A416 (2005) designates that the yield stress for low-relaxation strand should be above 90 percent of the ultimate stress. In other words, the required yield stress for grade 270 strand is 243 ksi and for grade 300 strand is 270 ksi.

The yield stresses were lower than expected for most strand types. Only grade 270 0.5 in. diameter regular strand did not have a test in which the measured yield stress was lower than that required by ASTM A416 (2005). In fact, 20 out of 41 measured yield stresses were below the required 90 percent of ultimate stress. Both strand size and grade show some correlation with the measured yield stress.

Table 4.7 Yield Stess Results for 0.5 in. Regular Strand

Test	Measured Yield Stress (ksi)	Minimum Yield Stress (ksi)	Ratio of Measured to Minimum Yield Stress
T.5R.270.A.1	252	243	1.03
T.5R.270.A.3	246	243	1.01
T.5R.270.A.4	249	243	1.02
T.5R.270.A.5	245	243	1.01
T.5R.270.A.6	249	243	1.02
Average	248	243	1.02
T.5R.300.A.1	269	270	1.00
T.5R.300.A.2	271	270	1.00
T.5R.300.A.3	272	270	1.01
T.5R.300.A.4	263	270	0.97
T.5R.300.A.5	268	270	0.99
T.5R.300.A.6	267	270	0.99
T.5R.300.A.7	277	270	1.03
T.5R.300.A.8	272	270	1.01
Average	270	270	1.00
T.5R.300.B.1	277	270	1.03
T.5R.300.B.2	276	270	1.02
T.5R.300.B.3	272	270	1.01
T.5R.300.B.4	274	270	1.01
T.5R.300.B.6	280	270	1.04
T.5R.300.B.8	282	270	1.05
T.5R.300.B.9	266	270	0.99
T.5R.300.B.10	276	270	1.02
Average	275	270	1.02

Both grade 270 and grade 300 0.5 in. regular strand from producer A exhibited acceptable yield stresses as shown in Table 4.7. As previously mentioned, all measured yield stresses in grade 270 regular strand were above the required yield from ASTM A416. The average yield stress for grade 270 0.5 in. regular strand was 248 ksi, or 2 percent higher than the minimum. Grade 300 strand from producer A had slightly lower yields with four tests below the required yield stress. However, three of the tests were less than 1 percent lower than 270 ksi, and the average was approximately equal to required yield stress. Grade 300 0.5 in. diameter super strand from producer B performed well with only one specimen out of eight that had a yield stress lower than 270 ksi and an average yield stress of 275 ksi.

The 0.5 in. diameter super strands had lower yield stresses than the 0.5 in. diameter regular strands. Of the 20 tests that failed to meet minimum yield stress, 13 of those were 0.5 in. diameter super strands. The measured yield stresses for 0.5 in. diameter super strands are shown in Table 4.8.

Table 4.8 Yield Stress Results for 0.5 in. Super Strands

Test	Measured Yield Stress (ksi)	Minimum Yield Stress (ksi)	Ratio of Measured to Minimum Yield Stress
T.5S.270.A.1	236	243	0.97
T.5S.270.A.2	242	243	1.00
T.5S.270.A.3	240	243	0.99
T.5S.270.A.4	236	243	0.97
T.5S.270.A.5	238	243	0.98
T.5S.270.A.6	242	243	1.00
T.5S.270.A.7	238	243	0.98
Average	239	243	0.98
T.5S.270.A2.1	231	243	0.95
T.5S.270.A2.3	242	243	1.00
T.5S.270.A2.4	235	243	0.97
T.5S.270.A2.6	235	243	0.97
Average	236	243	0.97
T.5S.300.A.1	265	270	0.98
T.5S.300.A.2	268	270	0.99
T.5S.300.A.3	274	270	1.02
T.5S.300.A.4	274	270	1.01
T.5S.300.A.5	269	270	1.00
T.5S.300.A.6	274	270	1.01
Average	270	270	1.00

For 0.5 in. diameter super strands, no test from either reel of grade 270 strand received from producer A had a measured yield stress that surpassed 90 percent of ultimate stress. In fact, one test from the second reel had a yield stress of 231 ksi, or 5.1 percent lower than the required stress. Despite no test surpassing the required yield stress, the averages for the first and second reel from manufacturer A were only 1.7 and 2.0 percent lower than the 243 ksi minimum stress. Half of the tested strands for grade 300 0.5 in. diameter super strands from manufacturer A had yield stresses that did not exceed 270 ksi—the required yield stress for grade 300 prestressing strand. The average yield stress, however, was the same as the minimum.

Table 4.9 Yield Stress Results for 0.6 in. Diameter Strand

Test	Measured Yield Stress (ksi)	Minimum Yield Stress (ksi)	Ratio of Measured to Minimum Yield Stress
T.6.270.A.1	247	243	1.01
T.6.270.A.2	242	243	0.99
T.6.270.A.6	238	243	0.98
Average	242	243	1.00

The measured yield stresses for grade 270, 0.6 in. diameter strand are shown in Table 4.9. Two of the three tests did not meet the minimum yield stress but were only 0.6 and 2.0 percent below 243 ksi. The average for the three tests is almost equal to the ASTM required yield stress.

Ninety percent of required ultimate stress was an accurate estimate of yield stress for all strands tested. The average yield stress for each type of strand was within 3 percent of this value and the overall average of the ratio of measured yield stress to required yield stress was 1.00. A summary of the measured yield stresses can be seen in Table 4.10.

Table 4.10 Summary of Yield Stress Results

Strand Type	Minimum (ksi)	Maximum (ksi)	Average (ksi)	Standard Deviation (ksi)	Required Yield Stess (ksi)	Ratio of Average to Required
5R.270.A	245	252	248	0.99	243	1.02
5R.300.A	263	277	270	1.73	270	1.00
5R.300.B	266	282	275	1.89	270	1.02
5S.270.A	236	242	239	2.30	243	0.98
5S.270.A2	231	242	236	2.75	243	0.97
5S.300.A	265	274	270	2.26	270	1.00
6.270.A	238	247	242	0.47	243	1.00

A lower yield stress than the required yield stress would have little effect on design. The main risk would be yielding the strand during prestressing. In most prestressing applications the strand is not stressed past 75 percent of ultimate stress, which is 202.5 ksi for grade 270 strand

and 225 ksi for grade 300 strand. Both of these stresses are well below the lowest measured yield stresses for both strands, which were 231 ksi and 265 ksi for grade 270 and grade 300 strand, respectively.

4.2.5 Ultimate Stress Analysis

The ultimate stress was calculated by dividing the maximum force in the strand during testing by the nominal area of the strand. It is very important that the strand meet the requirements of ASTM A416 (2005) for ultimate strength because a lower than expected breaking strength could result in a premature failure of a prestressed concrete member. ASTM A416 states that tests that fail in the grips and do not surpass the required strength should not be valid. However, the breaking strengths of the tests that failed in the grips were similar and in some cases higher than the tests with clear breaks. Therefore, all tests that failed in the grips were included in the results. The results of the ultimate stresses for 0.5 in. diameter regular strands are shown in Table 4.11.

Table 4.11 Ultimate Stress Results for 0.5 in. Diameter Regular Strands

Test	Measured Ultimate Stress (ksi)	Minimum Ultimate Stress (ksi)	Ratio of Measured to Minimum Ultimate Stress	Wires Broken
T.5R.270.A.1	278	270	1.03	7
T.5R.270.A.2	277	270	1.03	7
T.5R.270.A.3	279	270	1.03	7
T.5R.270.A.4	279	270	1.03	7
T.5R.270.A.5	279	270	1.03	7
T.5R.270.A.6	280	270	1.04	7
Average	279	270	1.03	
T.5R.300.A.1	302	300	1.01	7
T.5R.300.A.2	304	300	1.01	7
T.5R.300.A.3	302	300	1.01	7
T.5R.300.A.4	303	300	1.01	4
T.5R.300.A.5	299	300	1.00	6
T.5R.300.A.6	299	300	1.00	7
T.5R.300.A.7	303	300	1.01	7
T.5R.300.A.8	300	300	1.00	7
Average	301	300	1.00	
T.5R.300.B.1	298	300	0.99	2
T.5R.300.B.2	296	300	0.99	7
T.5R.300.B.3	297	300	0.99	1
T.5R.300.B.4	298	300	0.99	1
T.5R.300.B.5	295	300	0.98	1
T.5R.300.B.6	293	300	0.98	1
T.5R.300.B.7	293	300	0.98	7
T.5R.300.B.8	298	300	0.99	1
T.5R.300.B.9	294	300	0.98	4
T.5R.300.B.10	297	300	0.99	3
Average	296	300	0.99	

The results of the 0.5 in. diameter regular strands from producer A were as expected. The breaking strengths for both grades of strands had almost no scatter. All six of the tests performed on grade 270 0.5 in. diameter regular strand exceeded the guaranteed ultimate strength by 7 to 10 ksi, or around 3 percent. Tests T.5R.300.A.5 and T.5R.300.A.6 did not exceed the required strength, but were less than 1 percent low. While test 5 did fail in the grips, test 6 was a clean break between the grips and actually had a lower measured strength than test 6. In addition, the other strand that failed in the grips (test 4) had a strength that easily exceeded the guaranteed ultimate stress. The average rupture stress for grade 300 0.5 in. regular strands was 301 ksi. The grade 300 regular strand from producer B did not perform well. All ten of the tested strands had breaking stresses at least 2 ksi lower than the required ultimate stress from ASTM A416. Two specimens from producer B had rupture stresses of only 293 ksi and the average ultimate stress was 296 ksi, about 1 percent lower than the minimum required stress.

Table 4.12 Ultimate Stress Results for 0.5 in. Diameter Super Strands

Test	Measured Ultimate Stress (ksi)	Minimum Ultimate Stress (ksi)	Ratio of Measured to Minimum Ultimate Stress	Wires Broken
T.5S.270.A.1	264	270	0.98	7
T.5S.270.A.2	270	270	1.00	3
T.5S.270.A.3	267	270	0.99	7
T.5S.270.A.4	269	270	1.00	1
T.5S.270.A.5	265	270	0.98	7
T.5S.270.A.6	269	270	1.00	7
T.5S.270.A.7	267	270	0.99	7
Average	268	270	0.99	
T.5S.270.A2.1	268	270	0.99	7
T.5S.270.A2.2	274	270	1.01	7
T.5S.270.A2.3	274	270	1.02	7
T.5S.270.A2.4	273	270	1.01	7
T.5S.270.A2.5	272	270	1.01	7
T.5S.270.A2.6	275	270	1.02	1
Average	273	270	1.01	
T.5S.300.A.1	294	300	0.98	1
T.5S.300.A.2	294	300	0.98	6
T.5S.300.A.3	298	300	0.99	1
T.5S.300.A.4	298	300	0.99	1
T.5S.300.A.5	294	300	0.98	7
T.5S.300.A.6	298	300	0.99	7
Average	296	300	0.99	

Table 4.12 shows the recorded ultimate stresses for all 0.5 in. diameter super strands. The rupture stresses for three of the four types of super strands were not acceptable. The grade 270 strand from the first reel received by the producer had only one passing test out of seven. The test that passed had a rupture strength equal to the 270 ksi limit. The average for those seven strands was 268 ksi, or about 1 percent below the required breaking strength. The strand from the second reel of grade 270 0.5 in. diameter super strand performed much better. Only one

of the six tests had a measured rupture strength below 270 ksi. The other five tests exceeded the minimum stress by at least 2 ksi, and the average for all six tests was 273 ksi. Grade 300 0.5 in. diameter super strand exhibited poor breaking strengths. All 6 tests from manufacturer A had ultimate stresses at least 2 ksi below that required by ASTM A416. The strand from producer A had breaking stresses ranging from 294 to 298 ksi with an average of 269 ksi.

Although no test was more than 2.5 percent lower than the required strength, the low results are still cause for concern because such a large fraction of the strands failed before reaching the guaranteed ultimate strength. While neither grade of strand performed as it should have, grade 300 super strand did not perform as well as grade 270 strand. All 6 of the tests on grade 300 strand failed before reaching the required strength, whereas 5 of the 13 tests on grade 270 strand passed. In addition, the average maximum stress in grade 270 strand was equal to the required stress while the average for grade 300 strand was 4 ksi lower.

Many of the strands failed in the grips but were still included in the analysis. Their inclusion was justified because the highest stress for all four sets of strands occurred in a test that failed in the grips. Furthermore, the only set of tests in which the lowest strength was a failure in the grip was grade 300 strand from producer B, which had the same breaking strength as a 7-wire break between the grips.

The breaking stress results of the four grade 270 0.6 in. diameter strands tested to failure are shown in Table 4.13. The 0.6 in. diameter strand performed very well: it is the only size strand without a break below the minimum required strength. All four tests exceeded the required stress by at least 5 ksi and the average was 276 ksi. The results have virtually no scatter with rupture stresses varying by only 1 ksi, or 0.4 percent.

Table 4.13 Ultimate Stress Results for 0.6 in. Diameter Strand

Test	Measured Ultimate Stress (ksi)	Minimum Ultimate Stress (ksi)	Ratio of Measured to Minimum Ultimate Stress	Wires Broken
T.6.270.A.1	276	270	1.02	7
T.6.270.A.2	275	270	1.02	7
T.6.270.A.4	275	270	1.02	7
T.6.270.A.6	276	270	1.02	7
Average	276	270	1.02	

Table 4.14 Summary of Ultimate Stress Results

Strand Type	Minimum (ksi)	Maximum (ksi)	Average (ksi)	Standard Deviation (ksi)	Ratio of Average Stress to Required Stress
5R.270.A	277	280	279	0.99	1.03
5R.300.A	299	304	301	1.73	1.00
5R.300.B	293	298	296	1.89	0.99
5S.270.A	264	270	268	2.30	0.99
5S.270.A2	268	275	273	2.75	1.01
5S.300.A	294	298	296	2.26	0.99
6.270.A	275	276	276	0.47	1.02
Grade 270	264	280	273	4.78	1.01
Grade 300	293	304	298	3.23	0.99

The ultimate stress results are summarized in Table 4.14. A correlation between the ratio of breaking stress to required stress and strand grade was evident. The grade 270 strand performed well except for the first reel of 0.5 in. diameter super strand. The overall average for grade 270 strands was 273 ksi, or 1.2 percent over the required strength. Grade 300 strand, on the other hand, had at least two strands fail below guaranteed ultimate strength for each strand size, and two of the sets of strand did not have a test in which the required strength was achieved. The overall average for grade 300 strands was 298 ksi, or 0.7 percent below the required minimum.

All but two of the types of strand in this study had breaks below the minimum required by ASTM A416. In fact, three of the seven types of strands had an average strength lower than the minimum. If the rupture stress of a strand used in a prestressed concrete member is lower than the expected stress at nominal strength of the member, the member could fail prematurely. Therefore, it is imperative that prestressing strand have an ultimate stress greater than or equal to its expected strength.

4.2.6 Ultimate Elongation Analysis

ASTM A416 (2005) designates that the elongation of a strand at rupture should be at least 3.5 percent. Once again, if the strand broke in the grips ASTM A416 states that the result will not be valid; however, all of the strands had acceptable measured ultimate elongations. A large amount of slip occurred at the interfaces between the epoxy and the aluminum tubing and between the epoxy and the strand. During loading, the teeth in the grips induced deep indentations in the tubing, which decreased the amount of additional slip. Because of these indentions and a greater gripping force, the slip before yielding is much greater than the slip after yielding. Therefore, it is assumed in the ultimate elongation calculations that no slip occurs after the extensometer is removed. The elongation was determined with Equation 4-1 shown below:

$$\varepsilon_u = \frac{XHD_u - XHD_r}{L} + \varepsilon_{ext} \qquad 4\text{-}1$$

Where:

ε_u = ultimate strain in prestressing strand

XHD_u = crosshead displacement at rupture (in.)

XHD_r = crosshead displacement when extensometer was removed (in.)

L = gage length of strand (in.)

ε_{ext} = final strain measurement from extensometer

Table 4.15 Ultimate Elongation Results for 0.5 in. Diameter Regular Strands

Test	Calculated Ultimate Elongation	Wires Broken
T.5R.270.A.1	7.6%	7
T.5R.270.A.2	7.7%	7
T.5R.270.A.3	8.0%	7
T.5R.270.A.4	7.4%	7
T.5R.270.A.5	7.1%	7
T.5R.270.A.6	7.1%	7
Average	7.5%	
T.5R.300.A.1	7.1%	7
T.5R.300.A.2	7.3%	7
T.5R.300.A.3	7.2%	7
T.5R.300.A.4	7.9%	4
T.5R.300.A.5	6.6%	6
T.5R.300.A.6	7.4%	7
T.5R.300.A.7	7.4%	7
T.5R.300.A.8	6.0%	7
Average	7.1%	
T.5R.300.B.1	8.2%	2
T.5R.300.B.2	6.6%	7
T.5R.300.B.3	6.5%	1
T.5R.300.B.4	6.1%	1
T.5R.300.B.5	7.4%	1
T.5R.300.B.6	5.6%	1
T.5R.300.B.7	7.2%	7
T.5R.300.B.8	5.1%	1
T.5R.300.B.9	5.3%	4
T.5R.300.B.10	4.8%	3
Average	6.3%	

The elongations calculated using Equation 4-1 for 0.5 in. diameter regular strand are shown above in Table 4.15. Both strand grades performed very well. Every test on grade 270 strand more than doubled the required elongation. The average elongation for grade 270 0.5 in. diameter regular strand was 7.5 percent. Six of the eight calculated elongations for grade 300 strand from producer A doubled the required elongation while the other two tests had maximum elongations of 6.6 and 6.0 percent, well beyond that required. The average elongation for the grade 300 tests from producer A was 7.1 percent. The strand from manufacturer B had a lower average elongation and lower individual elongation than the grade 300 0.5 in. diameter regular strand from producer A. Four samples from producer B had calculated elongations lower than 6 percent with one measuring 4.8 percent. Nevertheless, the lowest elongation result of 4.8 percent is still well over the required elongation of 3.5 percent.

Table 4.16 Ultimate Elongation Results for 0.5 in. Diameter Super Strands

Test	Calculated Ultimate Elongation	Wires Broken
T.5S.270.A.1	6.6%	7
T.5S.270.A.2	7.4%	3
T.5S.270.A.3	7.2%	7
T.5S.270.A.4	7.2%	1
T.5S.270.A.5	7.1%	7
T.5S.270.A.6	7.3%	7
T.5S.270.A.7	7.3%	7
Average	7.2%	
T.5S.270.A2.1	7.3%	7
T.5S.270.A2.2	7.5%	7
T.5S.270.A2.3	7.7%	7
T.5S.270.A2.4	7.1%	7
T.5S.270.A2.5	7.1%	7
T.5S.270.A2.6	7.6%	1
Average	7.4%	
T.5S.300.A.1	5.8%	1
T.5S.300.A.2	5.2%	6
T.5S.300.A.3	7.8%	1
T.5S.300.A.4	9.7%	1
T.5S.300.A.5	7.3%	7
T.5S.300.A.6	7.4%	7
Average	7.2%	

All of the elongation results for 0.5 in. diameter super strands, shown above in Table 4.16, were well above the required 3.5 percent. Of the thirteen tests performed on strands from both reels of grade 270 strand, only one of them had an elongation less than 7 percent. The average elongations were 7.2 percent and 7.4 percent for the first and second reel received from producer A, respectively. The grade 300 0.5 in. diameter super strand performed well, but not as well as the grade 270 strands. The grade 300 strand had two samples with elongations less than 6 percent.

Table 4.17 Ultimate Elongation Results for 0.6 in. Diameter Strand

Test	Measured Ultimate Stress (ksi)	Wires Broken
T.6.270.A.1	7.4%	7
T.6.270.A.2	7.5%	7
T.6.270.A.6	7.5%	7
Average	7.5%	

Only three elongations were calculated for 0.6 in. diameter strand due to complications during testing. However, the results, shown in Table 4.17, were excellent. The three elongations were almost identical, differing by only 0.1 percent, and had an average elongation of 7.5 percent.

Table 4.18 Summary of Ultimate Elongation Results

Strand Type	Minimum	Maximum	Average	Standard Deviation	Ratio of Average to Required
5R.270.A	7.1%	8.0%	7.5%	0.35%	2.14
5R.300.A	6.0%	7.9%	7.1%	0.58%	2.03
5R.300.B	4.8%	8.2%	6.3%	1.10%	1.79
5S.270.A	6.6%	7.4%	7.2%	0.26%	2.04
5S.270.A2	7.1%	7.7%	7.4%	0.26%	2.11
5S.300.A	5.2%	9.7%	7.2%	1.59%	2.06
6.270.A	7.4%	7.5%	7.5%	0.06%	2.13
<7 wires broken	4.8%	9.7%	6.8%	1.04%	1.93
7 wires broken	6.0%	8.0%	7.3%	0.38%	2.07

A summary of the ultimate elongation results is shown in Table 4.18. Some correlation of elongation and strand size was present. The average elongations for both grade 270 and grade 300 were higher for 0.5 in. regular strand than for 0.5 in. diameter super strand. On the other hand, 0.6 in. diameter grade 270 strand had an average elongation the same as that calculated for 0.5 in. diameter regular strand of the same grade. For both 0.5 in. diameter regular and super strands, the average elongation is less for grade 300 strand than grade 270 indicating that grade 300 strand may be less ductile than grade 270 strand. This trend is expected as mild steel has a considerably larger ultimate elongation than prestressing strand, which is made of stronger steel.

The location of the failure exhibits some effect on the ultimate elongation of strand. The average elongation is 6.8 percent for those strands that failed in the grips compared to 7.3 percent for those that had a clean break between the grips. The failures due to notching in the grips also had lower individual values with a minimum of 4.8 percent elongation while the smallest elongation for a 7 wire break was 6.0 percent.

Strand rupture is a sudden failure and can result in complete collapse of a member. If strand rupture controls the design of a member, a greater ultimate elongation will provide a more ductile failure. Furthermore, in a member controlled by crushing of the concrete, the strand is expected to reach a certain elongation. All of the strands tested had measured elongations much greater than the 3.5 percent required by ASTM A416. Therefore, the strands should provide a sufficiently ductile failure in a prestressed concrete member.

4.2.7 Development of Stress-Strain Formulas

The stress-strain data for each set of tests was used to develop a formula to model the stress-strain behavior of that particular type of strand. The formula used is the same as that used by Devalapura and Tadros (1992) and is shown again below:

$$f_{ps} = \varepsilon_{ps}\left[A + \frac{B}{\left(1+\left(C\varepsilon_{ps}\right)^{D}\right)^{1/D}}\right] \qquad 4\text{-}2$$

Where:

f_{ps} = stress in the strand (ksi)

ε_{ps} = strain in the strand

A, B, C, D = constants used in power formula

The constants for each equation were determined by minimizing the sum of the squares of the errors along the stress-strain curve for each test. The constants for each type of strand are shown in Table 4.19. Also, the power formula is plotted along with the stress-strain curves for each strand type in

Figure 4.2 through Figure 4.8. The stress-strain curves for each strand type were very similar and showed little variation.

Table 4.19 Constants for Stress-Strain Power Formulas

Strand	A	B	C	D
5R.270.A	375.2	30162	118.2	5.306
5R.300.A	366.4	34132	122.5	5.466
5R.300.B	195.6	34224	120.2	5.148
5S.270.A	410.6	35730	147.6	4.163
5S.270.A2	448.9	25454	104.0	8.082
5S.300.A	226.6	33078	117.8	5.427
6.270.A	448.7	28845	116.6	6.905

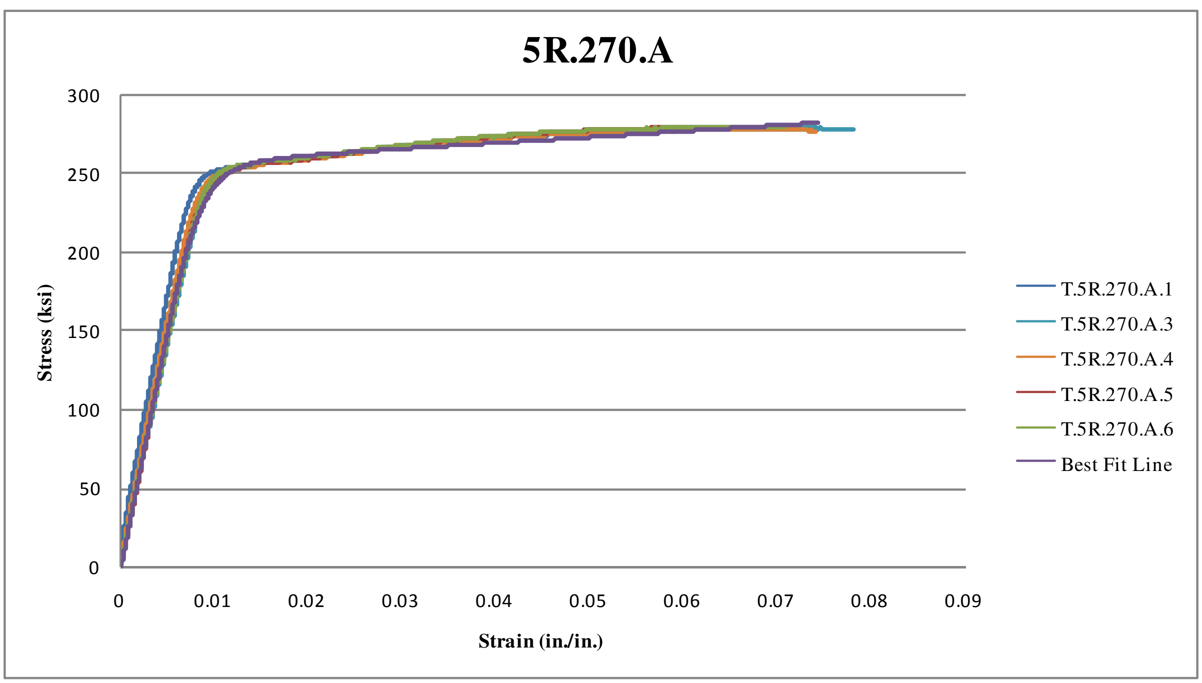

Figure 4.2 Stress-Strain Curves for 5R.270.A

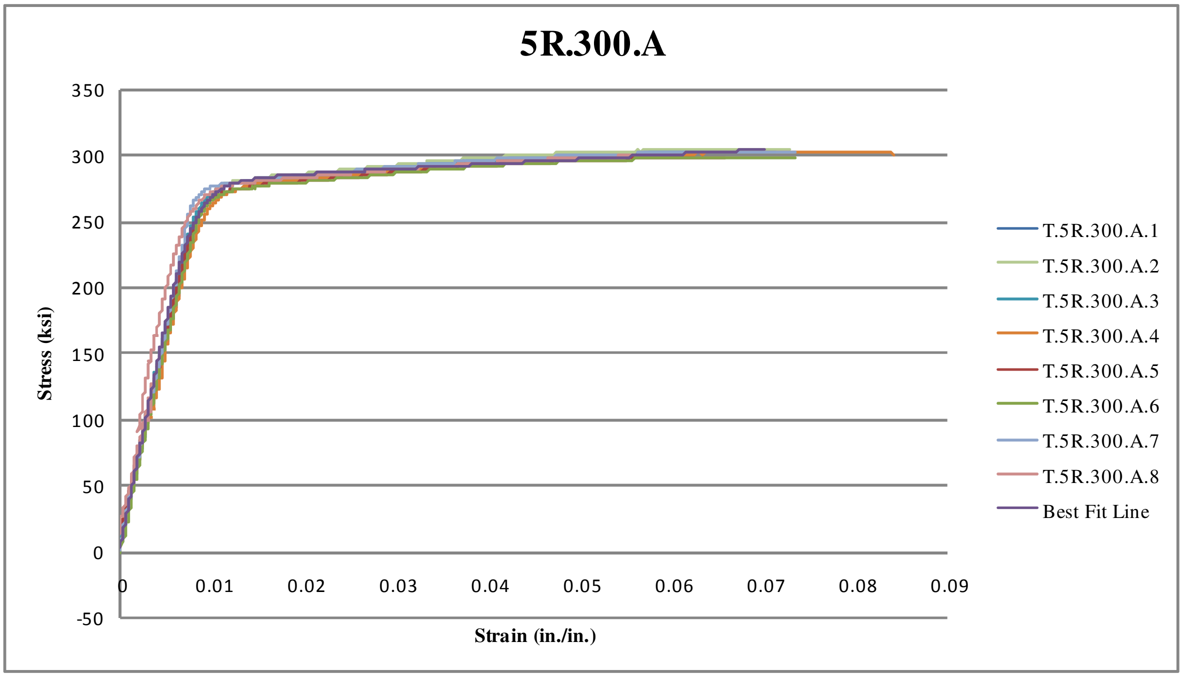

Figure 4.3 Stress-Strain Curves for 5R.300.A

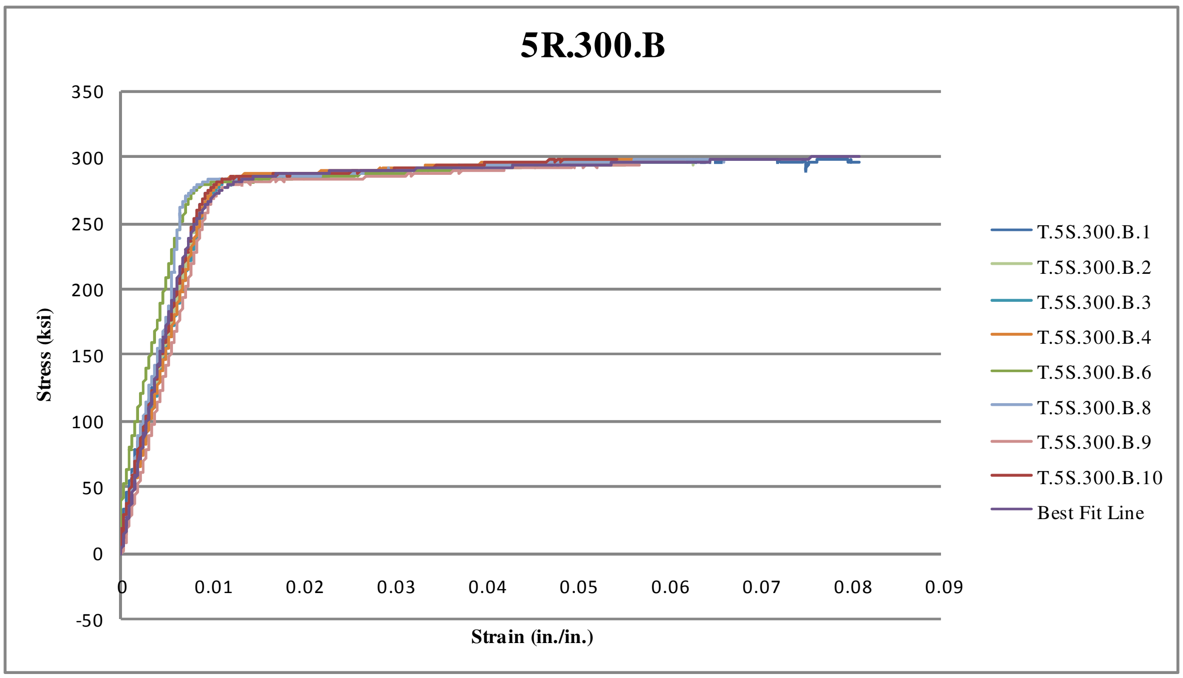

Figure 4.4 Stress-Strain Curves for 5R.300.B

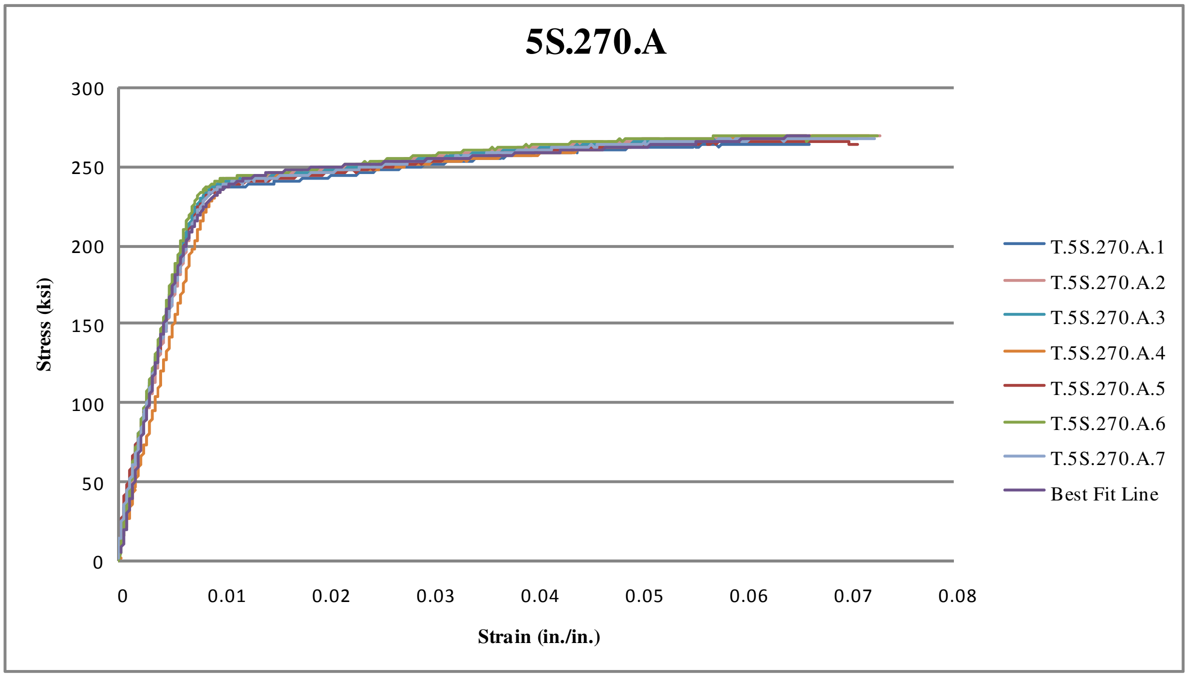

Figure 4.5 Stress-Strain Curves for 5S.270.A

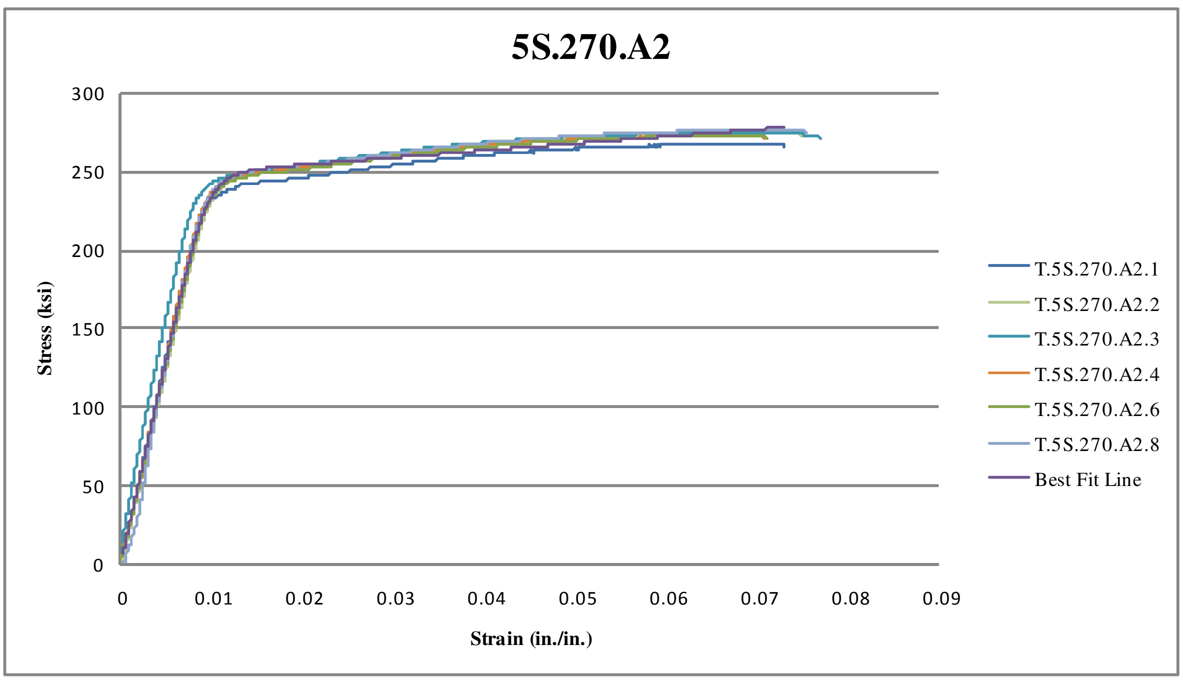

Figure 4.6 Stress-Strain Curves for 5S.270.A2

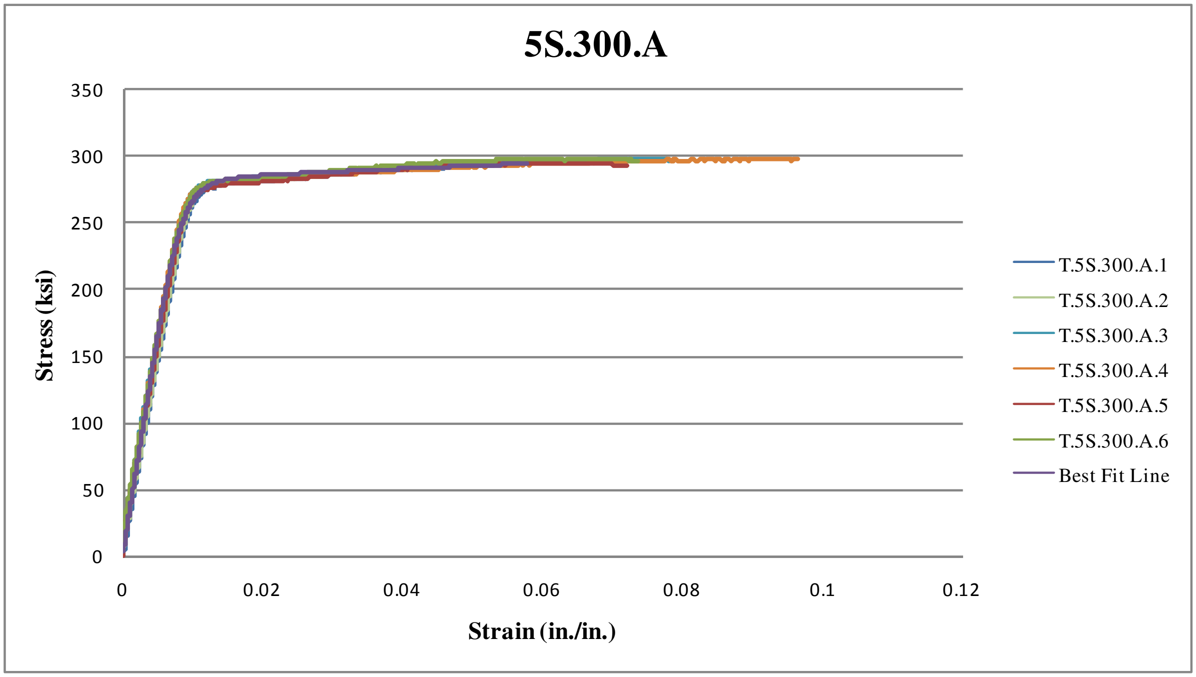

Figure 4.7 Stress-Strain Curves for 5S.300.A

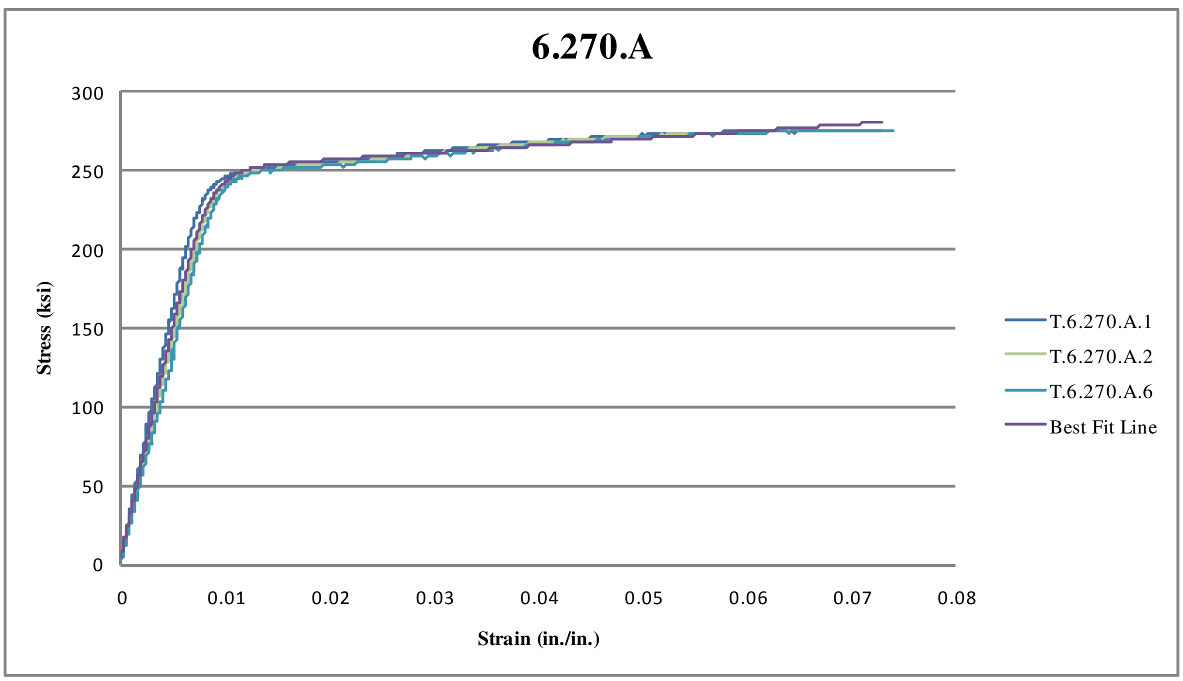

Figure 4.8 Stress-Strain Curves for 6.270.A

4.2.8 Tension Test Summary

Overall, most of the strands did not meet the requirements of ASTM A416 (2005). The ultimate stress for all sample must be greater than or equal 270 ksi for grade 270 strand. While provisions for grade 300 strand are not yet in place the ultimate stress should be greater than 300 ksi. The yield stress must be greater than or equal to 90 percent of the ultimate stress, which is 243 ksi for grade 270 strand and 270 ksi for grade 300 strand. Finally the total elongation of a gage length of at least 24 in. must be 3.5 percent or more. ASTM A416 states that if any specimen does not meet the requirements then the lot represented by the specimen can be rejected. Only grade 270 0.5 in. diameter regular strand did not have at least one specimen that failed the yield or ultimate stress requirements. Grade 270 0.6 in. strand was the only other strand that did not have at least one specimen that had a lower than acceptable ultimate stress. Table 4.20, shown below, depicts which sets of tests met or did not meet the requirements for both individual tests and the average for the set of tests. For the appropriate column, a P indicates that either all of the strands passed the requirements or that the average of the strands passed the requirements. An F indicates that either one or more of the individual tests did not meet the requirements or that the average of the tests did not meet the requirements.

Table 4.20 Strand Performance Versus ASTM A416 Requirements

Strand	Yield Stress		Ultimate Stress		Elongation	
	Indiv.	Avg.	Indiv.	Avg.	Indiv.	Avg.
5R.270.A	P (1.01)	P	P (1.03)	P	P	P
5R.300.A	F (0.97)	P	P (1.00)	P	P	P
5R.300.B	F (0.99)	P	F (0.98)	F	P	P
5S.270.A	F (0.97)	F	F (0.98)	F	P	P
5S.270.A2	F (0.95)	F	F (0.99)	P	P	P
5S.300.A	F (0.98)	P	F (0.98)	F	P	P
6.270.A	F (0.98)	F	P (1.02)	P	P	P
Value in parantheses: minimum ratio of actual to required stress						

4.3 Large Block Pullout Tests

Large Block Pullout Tests (LBPT's) were performed on 6 different types of strands for a total of 28 tests. Four strands were cast in each block. The fabrication of the blocks was done in two pours. The concrete strengths for the two pours at the time of testing were 6400 and 8100 psi for the first and second sets of blocks, respectively. The strands were tensioned until either the bond failed, the strand ruptured, or the test was stopped because the strand was near rupture. All of the bond failures took place after about 1 in. of slip. Also, all of the bond failures were abrupt failures that occurred after around 1 in. of slip.

4.3.1 Large Block Pullout Test Results

Load was measured for each test using a hollow load cell. The strand slip—the movement of the strand relative to the concrete—was monitored with a linear variable differential transformer (LVDT). The LVDT was removed for many of the tests because the plunger had no more travel or to prevent the LVDT from being damaged by a sudden failure. The LVDT was never removed before first slip occurred. Due to an uneven concrete surface, the frame tilted some during testing and the strand was not always loaded perpendicular to the surface of the concrete; however, the angle was never greater than around 5 degrees and therefore had little effect on the maximum load achieved. The tilt of the frame and the straightening of the strand made it difficult to predict from only the LVDT data when first slip occurred. However, the slip of the strand was visible to the naked eye and was accompanied by cracking of the concrete at the surface. The manually recorded data and the data collected from the LVDT were both used to determine the load at which first slip occurred. A typical load-displacement curve is shown in Figure 4.9. The first slip for this particular curve was determined to be 24 kips. The results from testing are shown below in Table 4.21 through Table 4.23.

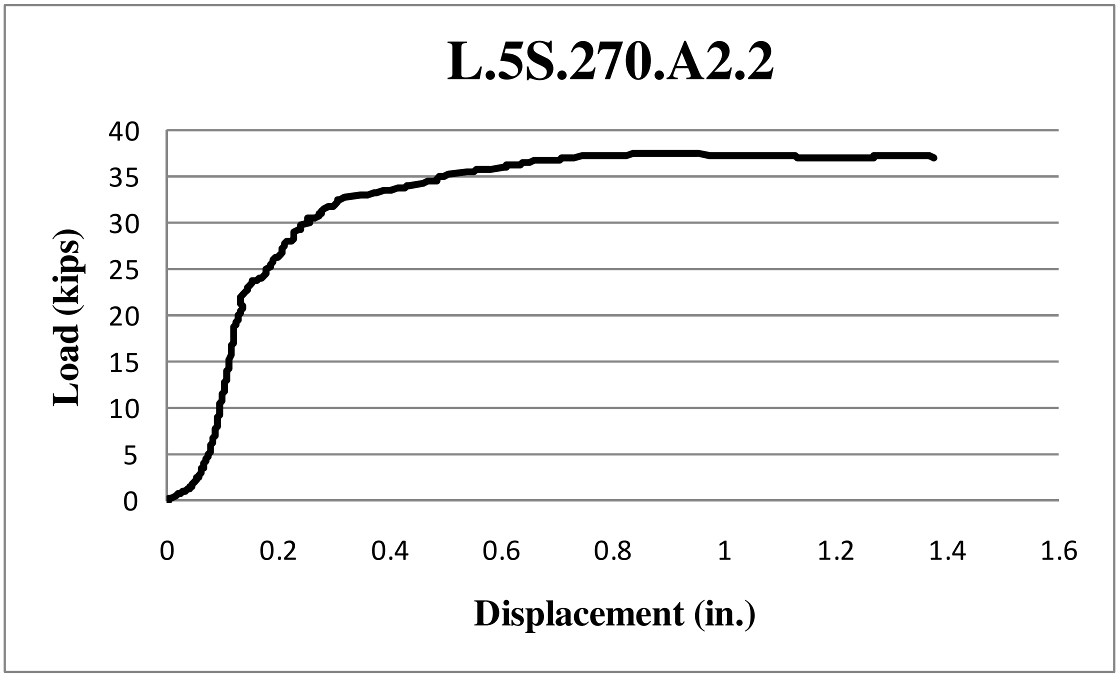

Figure 4.9 Load vs. Displacement Curve for L.5S.270.A2.2

Table 4.21 LBPT Results for 0.5 in. Diameter Regular Strand

Test	Load at First Slip (kips)	Maximum Load (kips)	Failure
L.5R.270.A.1	35	41.5	Bond
L.5R.270.A.2	24	41.6	Bond
L.5R.270.A.3	38	42.6	Stopped
L.5R.270.A.4	25	42.5	Stopped
Average	**31**	**42.1**	
St. Dev.	**7.05**	**0.58**	
f'c = 8100 psi			
L.5R.300.A.1	41	46.6	Bond
L.5R.300.A.2	42	44.9	Bond
L.5R.300.A.3	41	41.3	Bond
L.5R.300.A.4	31	41.3	Bond
Average	**39**	**43.5**	
St. Dev.	**5.19**	**2.66**	
f'c = 6400 psi			
L.5R.300.A.5	32	48.6	Strand
L.5R.300.A.6	21	41.1	Bond
L.5R.300.A.7	37	48.0	Stopped
L.5R.300.A.8	23	47.2	Bond
Average	**28**	**46.2**	
St. Dev.	**7.54**	**3.46**	
f'c = 8100 psi			

The results of the LBPT's for 0.5 in. diameter strand are shown above along with the mode of failure and the concrete strength of that particular block. All of the strands easily surpassed the minimum average load benchmark set by Logan (1997) of 36 kips. Two of the grade 270 strands had a bond failure at similar strengths of 41.6 kips and 41.5 kips, and the test was stopped for the two other strands to prevent strand rupture at 42.5 and 42.6 kips. All four of the tests in the first block containing grade 300 strand resulted in a bond failure. Despite weaker concrete, the average load for the grade 300 strand in the first block is slightly higher than the average load for the grade 270 0.5 in. diameter regular strands. However, it should be noted that two of the grade 270 tests were stopped before a bond failure occurred indicating that overall average would be higher than that shown. The grade 300 strands tested in the stronger concrete had the highest average pullout strength for 0.5 in. diameter regular strands. However, one of the tests had the lowest individual pullout strength of the regular strands at 41.1 kips. One other test had a bond failure at 47.2 kips while the other two tests reached the strand's strength before the bond failed. The loads at first slip for all three blocks was much more erratic than the maximum pullout force and did not seem to shown any correlation with the eventual pullout force.

Table 4.22 LBPT Results for 0.5 in. Diameter Super Strand

Test	Load at First Slip (kips)	Maximum Load (kips)	Failure
L.5S.270.A.1	37	38.9	Bond
L.5S.270.A.2	40	43.7	Bond
L.5S.270.A.3	30	46	Stopped
L.5S.270.A.4	37	45.2	Stopped
Average	**36**	**43.5**	
St. Dev.	**4.24**	**3.18**	
f'c = 8100 psi			
L.5S.270.A2.1	31	35.5	Bond
L.5S.270.A2.2	32	37.8	Bond
L.5S.270.A2.3	39	40.2	Bond
L.5S.270.A2.4	34	41.7	Bond
Average	**34**	**38.8**	
St. Dev.	**3.56**	**2.72**	
f'c = 8100 psi			
Test	Load at First Slip (kips)	Maximum Load (kips)	Failure
L.5S.300.A.1	47	50.1	Bond
L.5S.300.A.2	47	51.4	Strand
L.5S.300.A.3	38	47.9	Bond
L.5S.300.A.4	33	48.3	Bond
Average	**41**	**49.4**	
St. Dev.	**6.95**	**1.63**	
f'c = 8100 psi			

No benchmark for 0.5 in. diameter super strand has been proposed in previous research. Because 0.5 in. diameter super strand has 9 percent more area than regular strand, the force that must transferred to the concrete for a given stress level is 9 percent higher. Therefore, the pullout force should be 9 percent higher to get similar transfer and development length results. A 9 percent increase would change the required average pullout force from 36 kips to 39 kips.

The results of the LBPT's for 0.5 in. diameter super strands are shown above in Table 4.22. The strand that performed the best was the grade 300 super strand. All four of the maximum loads were at or above 48 kips. Three of the tests resulted in a bond failure, and in the other test the strand broke before the bond reached its ultimate strength. The strand from the first reel of grade 270 strand also performed well in the LBPT's. Two of the tests were stopped before a failure occurred, and the other two tests had bond failures of 38.9 and 43.7 kips. The average pullout strength was 43.5 kips, well over the proposed minimum average of 39.3 kips. The strand from the second reel of grade 270 strand did not perform as well, although it still surpassed the required load. All four tests resulted in a bond failure well below the breaking strength of the strand. The lowest recorded pullout force was 35.5 kips and the average pullout force was 38.8 kips, which is slightly under the minimum. Once again the loads at first slip were variable and showed little correlation to the strength.

Table 4.23 LBPT Results for 0.6 in. Diameter Strand

Test	Load at First Slip (kips)	Maximum Load (kips)	Failure
L.6.270.A.1	56	58.6	Strand
L.6.270.A.2	28	54	Bond
L.6.270.A.3	20	53.5	Bond
L.6.270.A.4	N/A	N/A	N/A
Avg	**35**	**55.4**	
St. Dev.	**18.9**	**2.81**	
f'c = 6400 psi			

No limit for an acceptable pullout force has been determined for 0.6 in. diameter strand. However, the results for this strand, shown above in Table 4.23, appear to be acceptable because all three recorded maximums approach the breaking strength of the strand. The 0.6 in. diameter strand has a 42 percent larger area than the 0.5 in. diameter regular strand, which means the force that must be transferred to the concrete is 42 percent higher. Therefore, the strand should have a 42 percent higher pullout force to expect similar transfer and development length results to 0.5 in. diameter regular strands. This ratio would increase the benchmark from 36 kips for 0.5 in. diameter regular strands (Logan 1997) to 51 kips for 0.6 in. diameter strand. Two of the tests had a bond failure at 54.0 and 53.5 kips while the third strand ruptured in the chuck at 58.6 kips. The fourth strand in this block had visible movement in the concrete before testing and pulled out at a very low strength. This could have been caused by the strand moving during curing or by poor consolidation. The results for this strand were omitted from the analysis. The average pullout force for the 0.6 in. diameter strands was 55.4 kips, which is around 5 percent higher than the proposed minimum of 51 kips.

4.3.2 Large Block Pullout Test Analysis

Overall the strands performed well in the Large Block Pullout Tests. Every strand had an average pullout force at least 2 kips over the minimum. The true average pullout force could not be determined for many of the strands because the test was limited by the strand strength rather than by the bond strength. A summary of the results is shown below in Table 4.24.

Table 4.24 Summary of LBPT Results

Strand	Average Maximum Load (kips)	Standard Deviation of Maximum Load (kips)	Concrete Strength (ksi)	Number of Bond Failures	Required Average Load (kips)	Ratio of Average to Required Load
5R.270.A	42.1	0.58	8100	2	36	1.17
5R.300.A	43.5	2.66	6400	4	36	1.21
5R.300.A	46.2	3.46	8100	2	36	1.28
5S.270.A	43.5	3.18	8100	2	39	1.11
5S.270.A2	38.8	2.72	8100	4	39	0.99
5S.300.A	49.4	1.63	8100	3	39	1.27
6.270.A	55.4	2.81	6400	2	51	1.09

As one would expect there is strong correlation between the size of the strand and the pullout force. Excluding the second reel of 0.5 in. diameter grade 270 super strand, the larger strand has a higher pullout force when compared to strands with the same grade steel. All of the strands initially received from producer A have average maximum loads very near their breaking strengths in only 18 in. of concrete. The pullout strengths for the second received reel of 0.5 in. diameter grade 270 super strand were noticeably lower. Because the same concrete and testing procedure was used for both sets of blocks for 0.5 in. diameter grade 270 super strand, the most likely cause for a different bond strength is a change in surface condition. These two results indicate that there may be differences in surface condition from strand received from the same producer.

A possible correlation exists between strand grade and bond strength. For both 0.5 in. diameter regular strand and 0.5 in. diameter super strand, the average maximum load for the LBPT is higher for grade 300 strand. In the two tests with the same strength concrete for 0.5 in. diameter regular strand both sets had two strands that were controlled by strand strength and not bond strength, indicating that the average strength would be higher for both sets of tests. The average pullout force for the grade 300 tests is about 4 kips, or 10 percent, higher than the force for grade 270 strand. A similar trend exists for the tests involving the 0.5 in. diameter super strands. The average for grade 300 super strand is 6 kips higher than the average for grade 270 strand. However, three bond failures occurred for the grade 300 tests while only two occurred for grade 270 super strand. Consequently, two of the grade 270 tests would have had a higher pullout force had bond controlled while this would be the case for only one of the tests on the stronger strand. Therefore, the difference between the pullout forces would probably be smaller than 6 kips had all tests resulted in a bond failure. Nonetheless, the pullout force for grade 300 0.5 diameter super strand would most likely still be higher than grade 270 strand.

The higher pullout forces for both sizes of strands may be caused by the strands' material properties. At such high loads the strands are well past yield. At any given load past yield for grade 270 steel, the strains will be higher in grade 270 strand than in grade 300. Higher strains in the steel would induce higher strains in the concrete, which could increase cracking and reduce bond strength between the concrete and the strand. These high forces would only exist in the strand near the surface of the concrete where enough force has not yet been transferred to the concrete to lower the stress in the steel below yield, which could explain why such a small difference exists in the pullout strengths.

4.3.3 Comparison of LBPT Results to Transfer and Development Lengths

Beams were cast using strand from the same reels as that used for the Large Block Pullout Tests at the Virginia Tech Structures and Materials Laboratory by Hodges (2006) and another researcher whose results have not yet been published. The beams had a "T" cross section and were cast with two beams per prestressing line. The prestress was released by flame cutting the strands between the two beams in each line. The transfer lengths were determined with the 95 percent average maximum strain method. The concrete strains were determined using detachable mechanical gage points and a 7.87 in. strain gage. The average transfer lengths shown in Table 4.25 are the average of transfer lengths from both the live and dead ends of all of the right side up beams that were tested. The development length ranges were determined by iteratively testing the beams in flexure at various embedment lengths. The maximum measured flexural bond length was added to the maximum measured transfer length to give the maximum development length, and the two minimums were added to give the minimum development length. Only the data for the right-side up beams was used for the analysis in this thesis. The transfer and development lengths determined from these beams were compared to the results of the LBPT's. The predicted transfer and development lengths were calculated with Equation 12-4 from ACI 318-05 with the assumptions of 67 or 75 percent initial prestress and 25 percent losses. A summary of these results is shown in Table 4.25. A plot of the ratio of the required maximum load to the average and the ratios of the predicted transfer and development lengths to the measured values is shown in Figure 4.10.

Table 4.25 Comparison of LBPT Results to Transfer and Development Lengths

Strand	Average Maximum Load (kips)	Average Transfer Length (in.)	Initial Prestress (%)	ACI 318-05 Predicted Transfer Length (in.)	Minimum Development Length (in.)	Maximum Development Length (in.)	ACI 318-05 Predicted Development Length (in.)
5R.270.A	42.1	14.3	67	23	N/A	66.5	90
5R.300.A	44.9	16.3	67	25	42	66	100
5S.270.A	43.5	17.1	67	23	49.5	69.5	90
5S.270.A	43.5	16.8	75	25	49.5	69.5	84
5S.270.A2	38.8	19.0	75	25	51	63	84
5S.300.A	49.4	17.1	67	25	52.5	78.5	100
5S.300.A	49.4	17.5	75	28	52.5	78.5	94
6.270.A	55.4	15.3	75	30	61	71	101

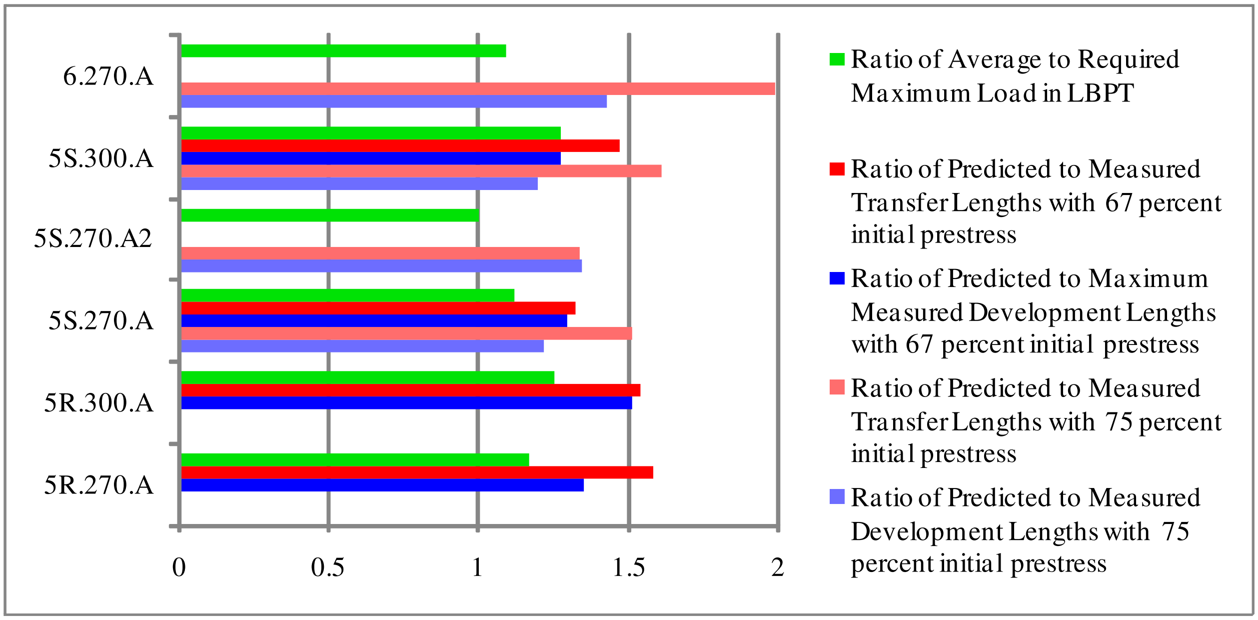

Figure 4.10 Comparison of LBPT Results to Transfer and Development Lengths

The results of the LBPT's and the transfer and development lengths correlated well. The average pullout forces were at or above the minimum for all the strands tested. Strand with pullout forces higher than this minimum should have adequate transfer and development lengths. All of the strands had transfer and development lengths well below those predicted by ACI 318-05 indicating that the LBPT is an acceptable measure of strand surface condition. Furthermore, the transfer and development lengths indicate that the minimum average pullout forces of 36, 39, and 51 kips are conservative benchmarks for the 0.5 in. diameter regular strand, 0.5 in. diameter super stand, and 0.6 in. diameter strand used in this research. The benchmark of 39 kips for 0.5 in. diameter super strand seemed to produce similar results as the 36 kips benchmark for 0.5 in. diameter regular strand. The ratio of predicted to actual transfer and development lengths was greater than the ratio of actual to required pullout strengths for all of the strands except for the grade 300 0.5 in. diameter super strand. The transfer lengths for the beams with 75 percent initial prestress had a ratio slightly below the ratio for the LBPT. The benchmark of 51 kips for

0.6 in. diameter appears to be more conservative than the 36 kips benchmark for regular strand. The ratios for predicted to actual transfer and development lengths is 1.43 and 1.97 while the LBPT actual to required ratio is only 1.09. However, this is a small data set as there was only one right side up beam cast with 0.6 in. diameter strand.

The second reel of 0.5 in. diameter grade 270 super strand had a significantly lower average pullout force than the first reel of the same strand. The average measured transfer length for the second reel is 2 in. longer than that for the first reel indicating that strand 5S.270.A2 may have a poorer bond quality than 5S.270.A. On the other hand, the maximum development length for the second reel is lower than that for the first reel, which contradicts the transfer length comparison.

4.3.4 Further Discussion of Large Block Pullout Test Results

In some of the tests unusually high forces were achieved in the strands. The recorded forces were actually higher than the breaking forces from the tension tests. The tests where this occurred are shown in Table 4.26.

Table 4.26 LBPT Results versus Tension Test Results

Test	Maximum Load in LBPT (kips)	Maximum Load in Tension Tests (kips)	Ratio
L.5R.300.A.5	48.6	46.5	1.05
L.5R.300.A.7	48.0	46.5	1.03
L.5R.300.A.8	47.2	46.5	1.02
L.5S.270.A.3	46.0	45.2	1.02
L.5S.300.A.2	51.4	49.8	1.03

Higher loads from the LBPT's than from the tension tests are counterintuitive. The strands should have failed sooner in tension during the LBPT's because they were gripped with a prestressing chuck. The teeth of the chuck dug into the strand, lowering the cross-sectional area and creating stress concentrations. During the tension tests, the strands were cushioned from notching and many of the failures broke all 7 wires at the same time. No explanation for the higher loads could be determined.

4.4 NASP Tests

A set of six tests was performed on each of six different types of strands for a total of 36 tests. Load and free end slip were monitored throughout the tests. The strands were tensioned until the load could no longer be increased or until the free end slip reached around 1.5 in. Plots of the load vs. live end displacement and dead end slip are shown in Appendix B. The live end of the strand was the end being loaded and the dead end (free end) was not loaded. The load vs. displacement plot for test N.5R.270.A.2 is shown in Figure 4.11 to provide a typical plot.

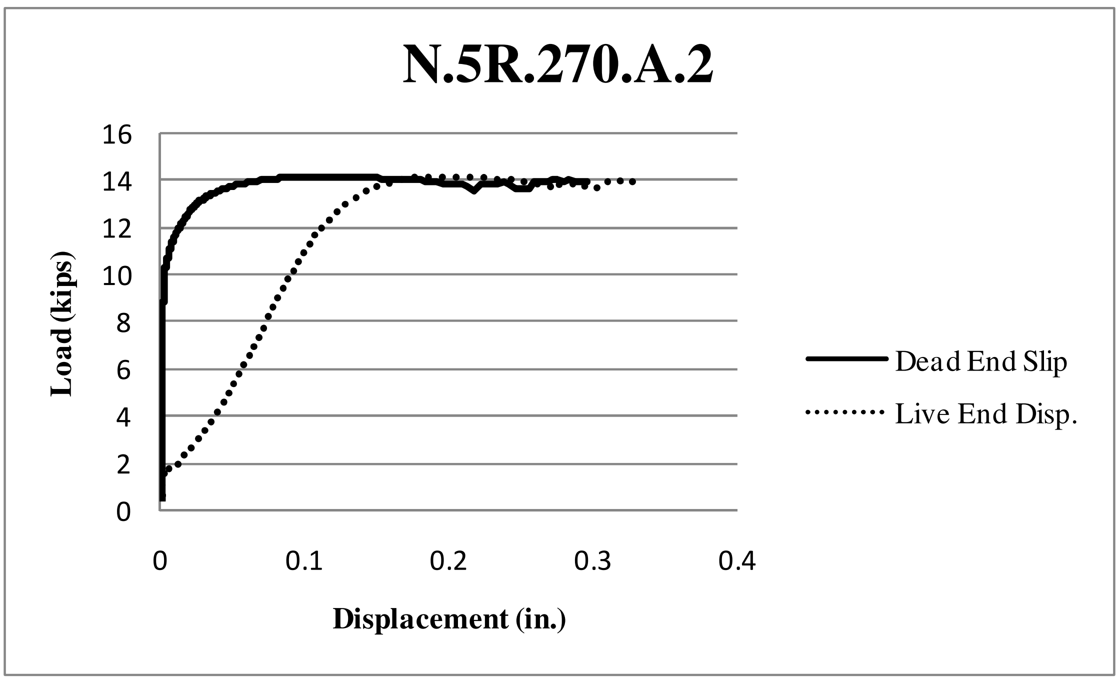

Figure 4.11 Load-Displacement Plot for N.5R.270.A.2

4.4.1 NASP Test Results

As noted in Chapter 3 there were some complications with the grout mix. Tests N.5R.270.A.1-6 and N.5S.270.A2.1-6 were made with the same mix proportions but the mix used for the regular strand had cement A and sand A while cement B and sand B were used for the super strand. The mix proportions for all of the tests are shown in Table 3.2. The mix for the other four sets was initially designed to obtain a strength between the limits of 4500 and 5000 psi. However, this strength was not obtained for many of the tests. Each set of tests took about 2 to 3 hours to perform. The grout strength measured in the middle of this time period is shown for each set of tests in its corresponding table in Table 4.27 through Table 4.29. The mix proportions were not changed after the first test with the new mix so that the strands would be tested in similar strength grout. The desired value from the NASP Test is the load at 0.1 in. of dead end slip. This value, known as the NASP Bond Test Value, and the maximum load are shown in the tables below for each test. Surface cracking did not occur in any of the tests.

Table 4.27 NASP Test Results for 0.5 in. Diameter Regular Strand

Test	Load at 0.1 in. Slip (kips)	Maximum Load (kips)	Ratio of NASP Value to Required Value, 10.5 kips
N.5R.270.A.1	12.0	14.5	1.14
N.5R.270.A.2	14.1	14.1	1.34
N.5R.270.A.3	14.8	17.4	1.41
N.5R.270.A.4	15.6	16.6	1.49
N.5R.270.A.5	16.9	17.2	1.61
N.5R.270.A.6	14.4	15.3	1.37
Average	**14.6**	**15.8**	**1.39**
St. Dev.	**1.51**	**1.29**	
f'c = 4492 psi			
flow = 123			
N.5R.300.A.1	10.2	13.8	0.97
N.5R.300.A.2	13.5	16.5	1.29
N.5R.300.A.3	12.7	16.9	1.21
N.5R.300.A.4	13.9	17.9	1.33
N.5R.300.A.5	12.3	13.7	1.17
N.5R.300.A.6	12.4	15.1	1.18
Average	**12.5**	**15.7**	**1.19**
St. Dev.	**1.21**	**1.57**	
f'c = 4333 psi			
flow = 115			

The NASP Test results for both grades of 0.5 in. diameter regular strand are shown in Table 4.27. During the first test for grade 270 0.5 in. diameter strand, the plunger in the LVDT stuck. However, using the crosshead displacement data and comparing the plots with the other five tests an estimate of when 0.1 in. of slip was made. The load was almost constant for crosshead displacements from 0.1 in. to 0.3 in. and actually decreased some. Therefore, the NASP Bond Test Value could easily be estimated. The results are somewhat erratic with standard deviations for both sets of data around 10 percent of the average. However, both sets of data contain one test that is significantly lower than the other five thus increasing the standard deviation by a large amount. The loads at 0.1 in. of slip for the grade 270 strand are consistently higher than the loads for the grade 300 regular strand. The average NASP Bond Test Value for the lower grade strand is 17 percent higher than that for grade 300 strand. The maximum loads, however, are virtually identical varying by only 1 percent. The maximum values are around 10 percent and 25 percent higher than the NASP Values for grade 270 and grade 300 strand, respectively. Both sets of strands are well over the required average NASP Value of 10.5 kips. Eleven of the twelve tests had a NASP Value at least 30 percent higher than the minimum for an individual test (9.0 kips).

Table 4.28 NASP Test Results for 0.5 in. Diameter Super Strand

Test	Load at 0.1 in. Slip (kips)	Maximum Load (kips)	Ratio of NASP Value to Required Value, 11.5 kips
N.5S.270.A.1	13.9	16.9	1.21
N.5S.270.A.2	13.8	22.4	1.20
N.5S.270.A.3	12.8	15.8	1.11
N.5S.270.A.4	13.8	16.3	1.20
N.5S.270.A.5	15.5	18.6	1.35
N.5S.270.A.6	13.9	19.9	1.20
Average	**14.0**	**18.3**	**1.21**
St. Dev.	**0.78**	**2.28**	
f'c = 4363 psi			
flow = 111			
N.5S.270.A2.1	9.8	18.4	0.86
N.5S.270.A2.2	9.6	16.6	0.84
N.5S.270.A2.3	10.4	15.6	0.90
N.5S.270.A2.4	11.3	15.3	0.98
N.5S.270.A2.5	9.9	16.1	0.86
N.5S.270.A2.6	9.2	14.8	0.80
Average	**10.0**	**16.1**	**0.87**
St. Dev.	**0.67**	**1.18**	
f'c = 4017 psi			
flow = 115			
N.5S.300.A.1	14.7	20.7	1.28
N.5S.300.A.2	13.4	20.8	1.17
N.5S.300.A.3	16.6	23.4	1.45
N.5S.300.A.4	14.3	23.9	1.24
N.5S.300.A.5	12.9	24.0	1.12
N.5S.300.A.6	15.7	24.0	1.37
Average	**14.6**	**22.8**	**1.27**
St. Dev.	**1.28**	**1.45**	
f'c = 4533 psi			
flow = 111			

The plunger in the LVDT stuck in test N.5S.270.A2.3. The NASP Value was estimated by comparing the crosshead displacement versus load plots to the other five tests. Similarly to the LBPT, the required NASP Value of 0.5 in. diameter super strands could be increased from that required for regular strands by the ratio of the areas. Because super strand has a larger area, the force that must be transferred to concrete is larger. This ratio would increase the minimum average NASP Value to 11.5 kips and the minimum value for a single test to 9.8 kips. The NASP Test results for 0.5 in. diameter super strand are shown in Table 4.28. The strand from the first received reel of grade 270 performed very well. The average load at 0.1 in. of slip was almost 14 kips, which is around 20 percent higher than the minimum. Also, there is relatively little scatter with a standard deviation of only 5.6 percent of the average. The grade 300 strand also performed well with an average NASP Value of 14.6 kips, or 27 percent above the proposed required strength. The grade 270 strand from the second reel did not perform as well. Two of the tests had NASP Values below the minimum for an individual strand and the average value was only 10.0 kips, which is below the required 11.5 kips. However, the grout strength for that set of tests was significantly lower than the required compressive strength range of 4500 to 5000 psi. This issue will be discussed in greater detail later in this chapter. The ratio of maximum loads to NASP Values were much higher for the 0.5 in. diameter super strands than the ratio for the regular strand. The greatest difference was found in the grade 270 strand from the second reel and the grade 300 strand which had average load increases of 61 and 56 percent past the load at 0.1 in. of slip. The load in tests N.5S.270.A2.1 and N.5S.300.A.5 almost doubled after 0.1 in. of slip occurred.

Table 4.29 NASP Test Results for 0.6 in. Diameter Strand

Test	Load at 0.1 in. Slip (kips)	Maximum Load (kips)	Ratio of NASP Value to Required Value, 12.6 kips
N.6.270.A.1	17.2	24.8	1.37
N.6.270.A.2	16.6	25.6	1.32
N.6.270.A.3	17.3	21.3	1.37
N.6.270.A.4	16.9	29.9	1.34
N.6.270.A.5	17.3	28.0	1.37
N.6.270.A.6	14.5	20.7	1.15
Average	**16.6**	**25.1**	**1.32**
St. Dev.	**0.99**	**3.31**	
f'c = 4333 psi			
flow = 108			

The NASP Test results for 0.6 in. diameter strand are shown above. The minimum average NASP Value for 0.6 in. strand is 12.6 kips (Ramirez and Russell 2007). The strand performed well with all of the NASP Values between 16.5 and 17.5 kips except for test 6, which was significantly lower at 14.5 kips. The minimum for an individual test for 0.6 in. strand is 10.8 kips. The average load at 0.1 in. of slip was 30 percent higher than the required average of 12.6 kips. The 0.6 in. diameter strand also saw a large increase in load after 0.1 in. of slip with an average increase of 51 percent and an increase in test 4 of 78 percent.

4.4.2 NASP Test Analysis

The grout strengths for most of the NASP Tests were not in the required range of 4500 to 5000 psi. However, all but one of them were within 200 psi of the range. Ramirez and Russell (2007) found that the NASP Test Value is proportional to the square root of the compressive strength of the grout. Therefore, to normalize the data, the NASP Values for all six types of strand were modified by multiplying the value by the square root of the quotient of the compressive strength of the grout divided by 4500 psi. The original and normalized averages are shown below in Table 4.30.

Table 4.30 Summary of NASP Test Results

Strand	Average NASP Value (kips)	f'c (psi)	Normalized NASP Value (kips)	Required NASP Value (kips)	Ratio of Normalized to Required Value
T.5R.270.A	14.6	4500	14.6	10.5	1.39
T.5R.300.A	12.5	4333	12.7	10.5	1.21
T.5S.270.A	14.0	4363	14.2	11.5	1.23
T.5S.270.A2	10.0	4017	10.6	11.5	0.92
T.5S.300.A	14.6	4533	14.6	11.5	1.27
T.6.270.A	16.6	4333	16.9	12.6	1.34

Despite an increase from the strength ratios, the NASP Value for the second reel of 0.5 in. diameter super strand is still significantly lower than all of the other strands. Furthermore, the adjusted NASP Value is still 8 percent below the proposed requirement of 11.5 kips. The other strand that is noticeably lower than the others is the grade 300 0.5 in. regular strand. Its normalized average is 12.8 kips, which is still well above the requirement.

Some correlation does exist between the size of the strand and the NASP Value. As one would expect, the largest adjusted average NASP Value is the force for 0.6 in. diameter strand. The ratio of its measured NASP Value to the required value is 1.34, which is approximately the same as the same ratios for four of the other strands. There was no obvious increase in NASP strength between the regular and super strands. For grade 270, the regular strand had a higher value while for grade 300, the super strands normalized NASP value was highest. The same case was true when the two strand grades were compared. The grade 270 strand had a higher NASP Value for the regular strand while the grade 300 0.5 in. diameter super strand had a higher strength than the grade 270 super strand.

4.4.3 Comparison of NASP Test Results to Transfer and Development Lengths

The same transfer and development length values used in Section 4.3.3 in comparison to the LBPT's were compared to the NASP Test results. The measured transfer and development lengths were obtained from beams using strands from the same reels as those used for the NASP Test. Predicted values were calculated according to ACI 318-05. The normalized NASP Values and transfer and development lengths are shown in Table 4.31. A comparison of the ratio of the average NASP Value to the required values and the ratios of the predicted transfer and development lengths to the measured lengths is shown in Figure 4.12.

Table 4.31 Comparison of NASP Test Results to Transfer and Development Lengths

Strand	Normalized NASP Value (kips)	Average Transfer Length (in.)	Initial Prestress (%)	ACI 318-05 Predicted Transfer Length (in.)	Minimum Development Length (in.)	Maximum Development Length (in.)	ACI 318-05 Predicted Development Length (in.)
5R.270.A	14.6	14.3	67	23	N/A	66.5	90
5R.300.A	12.7	16.3	67	25	42	66	100
5S.270.A	14.2	17.1	67	23	49.5	69.5	90
5S.270.A	14.2	16.8	75	25	49.5	69.5	84
5S.270.A2	10.6	19.0	75	25	51	63	84
5S.300.A	14.6	17.1	67	25	52.5	78.5	100
5S.300.A	14.6	17.5	75	28	52.5	78.5	94
6.270.A	16.9	15.3	75	30	61	71	101

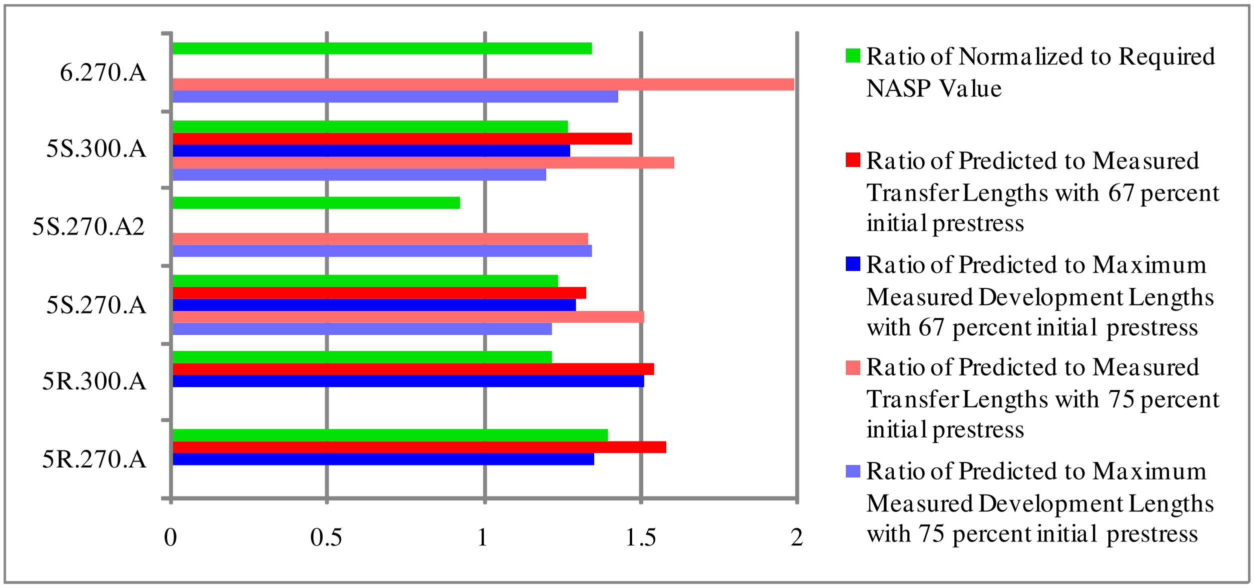

Figure 4.12 Comparison of NASP Test Results to Transfer and Development Lengths

Six of the seven strands had normalized NASP Values higher than the minimum average, which should indicate that the transfer and development lengths were below the predicted values. In fact, the transfer and development lengths for the strand types were all at least 20 percent lower than the values predicted by ACI 318-05. Furthermore, strand from the second reel of 0.5 in. diameter super strand had a NASP Value lower than the required 11.5 kips but still had transfer and development lengths lower than the predicted values. Therefore, the minimum NASP Value was conservative and the NASP Test was an acceptable measure of strand surface condition for these strands. The lowest NASP Value was that for the second reel of grade 270 super strand. This strand also had the longest transfer length, which would indicate further that the NASP Test can accurately measure surface condition. However, the maximum development length for the second reel of super strand was higher than the maximum development length for strand from the first reel. The fact that 5S.270.A2 failed the NASP Test but still had conservative transfer and development lengths may indicate that the value of 11.5 kips may be overly conservative. The other two super strands had ratios of actual to predicted transfer and development lengths similar to the ratios of actual to required NASP values, which would indicate that the required value of 11.5 kips is an acceptable benchmark.

4.5 Comparison of NASP Test and LBPT

Both the North American Strand Producers (NASP) Bond Test and Larger Block Pullout Test (LBPT) performed well. Five of the six strands tested had values from both tests above the minimums, and all of the transfer and development lengths were below the predicted values. The averages for each strand are shown below in Table 4.32.

Table 4.32 Comparison of LBPT to NASP Test

Strand	Average Maximum Load from LBPT (kips)	Normalized NASP Value (kips)	Ratio of LBPT to NASP
5R.270.A	42.1	14.6	2.87
5R.300.A	44.9	12.7	3.52
5S.270.A	43.5	14.2	3.07
5S.270.A2	38.8	10.6	3.66
5S.300.A	49.4	14.6	3.40
6.270.A	55.4	16.9	3.27

The values for both tests show similar trends. The highest pullout force test for each test is the force for 0.6 in. diameter strand, which is to be expected because the strand has a greater surface area. The lowest pullout strength for both tests was for the strand from the second reel of 0.5 in. diameter super strand. The benchmarks for both tests were conservative for all of the sets of strand used in this reserach. Overall, the values correlated fairly well with an average ratio around 3.3. The two sets of data were plotted and a best fit line was determined using linear regression. The data showed fair correlation with a coefficient of determination of 0.7. The plot and best fit line are shown in Figure 4.13.

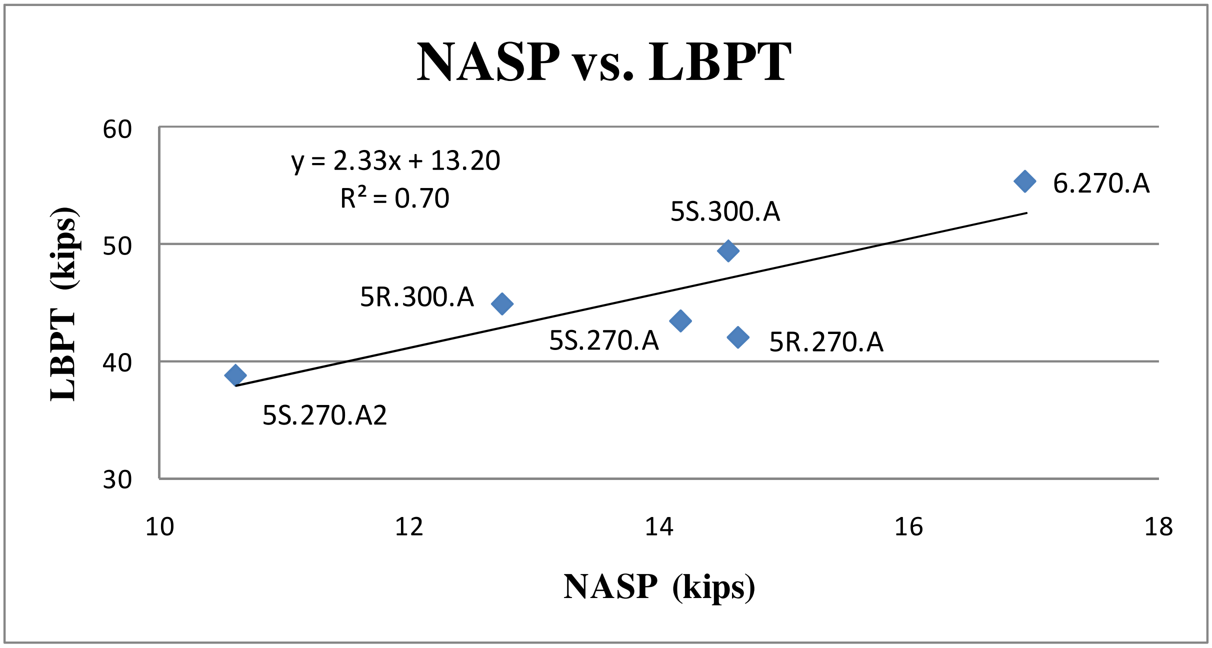

Figure 4.13 Plot of NASP Results vs. LBPT Results

Table 4.33 Comparison of Scatter for LBPT and NASP Test

Strand	Average Maximum Load from LBPT that Failed in Bond (kips)	Standard Deviation of LBPT that Failed in Bond (kips)	Coefficent of Variance	Normalized NASP Value (kips)	Standard Deviation of LBPT that Failed in Bond (kips)	Coefficient of Variance
5R.270.A	41.6	0.07	0.00	14.6	1.51	0.10
5R.300.A	43.7	2.84	0.06	12.7	1.21	0.09
5S.270.A	41.3	3.39	0.08	14.2	0.78	0.06
5S.270.A2	38.8	2.72	0.07	10.6	0.67	0.06
5S.300.A	48.8	1.17	0.02	14.6	1.28	0.09
6.270.A	53.8	0.35	0.01	16.9	0.99	0.06

The relative scatter for each set of pullout tests is shown in Table 4.33. Only the LBPTs that failed in bond are included in Table 4.33 so that the scatter will reflect only the bond strength of each test, not the strength of the strand. Overall the scatter for the Large Block Pullout Tests was lower than that for NASP Tests. However, the data sets for the LBPTs were much smaller. The LBPTs with the two lowest coefficients of variance had only two tests that had a bond failure. Another possible reason for the greater scatter in the NASP Tests is that the values were much smaller. The measured loads were only accurate to with a few tenths of a kip, which would have a greater effect on a smaller load. Nonetheless, the LBPT had at least the same amount of scatter if not less than the NASP Tests for the strands tested in this research.

The grout mix made the NASP Test difficult to perform. Type III cement can be hard to find in some areas and may be expensive if shipped a long distance. Because of the strict strength and flow ranges, the sensitivity of the mix proportions, and the narrow range for curing time, an initial grout mix is difficult to obtain. On the other hand, it is easier to mix the small amounts of grout needed for the NASP Tests than to mix the amount of concrete needed for LBPT's if mixing in a lab. Furthermore, if the concrete for the blocks is ordered from a batch plant, it is difficult to obtain a consistent mix with the desired material properties, which influence the results. In the LBPT's, the strand can be tested in the same concrete as that used in the beams that will use the same strand. However, this is not always possible at a prestressing plant.

The preparation for the concrete placement is equally difficult for both tests. In the NASP Test, the steel must be cut and welded each time a test is performed. The formwork can be reused for LBPT's, but the mild reinforcement and strands must be tied in place for each test. The procedure for both tests is fairly easy and both tests last only a few minutes. Overall, both tests were good standard tests for the assessment of strand surface condition, but the LBPT was much easier to perform because of the difficulty of the grout mix required for the NASP Bond Test.

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

Tension tests and two types of pullout tests were performed at the Virginia Tech Structures and Materials Laboratory. The research was part of a larger project sponsored by the Virginia Transportation Research Council and the Virginia Department of Transportation to investigate the performance of the new grade 300 prestressing strand. The two main objectives of this thesis were to determine the material and bond properties of grade 270 and grade 300 prestressing strand.

The material properties were investigated by tensioning the strands to failure. From the stress and strain in the strand, the modulus of elasticity, yield stress, ultimate stress, and ultimate elongation were calculated. The bond properties were investigated through two untensioned pullout tests. In the North American Strand Producers (NASP) Bond Test a strand was cast in a 5 in. diameter, 18 in. long, grout-filled can and tensioned to failure. The other pullout test was the Large Block Pullout Test where four strands were cast into a 2 ft. cube of concrete and tensioned to failure. The results of both of these tests were compared to transfer and development length tests performed in another portion of this project to investigate the performance of each test as a standard to investigate strand surface condition.

5.2 Conclusions and Recommendations

5.2.1 Tension Tests

- The aluminum tubing and epoxy mix were an excellent gripping system. Most strands broke between the grips and even when a strand broke in the grips a ductile failure occurred.

- The measured modulus of elasticity was higher and more erratic for grade 300 strand than for grade 270 strand. The average modulus of elasticity for all grade 300 strands was 29,600 ksi with results ranging from 27,700 ksi to 34.600 ksi.
- The yield stress results were lower than expected, especially for 0.5 in. diameter super strands. Six of the seven types of strand had at least one measured yield stress lower than the required minimum from ASTM A416 (2005). Furthermore, none of the grade 270 0.5 in. diameter super strands tested had a yield stress higher than the minimum. Overall, the grade 300 strand had higher proportional yield stresses than the grade 270 strand.
- The ultimate stress was acceptable for 0.5 in. diameter regular strand and 0.6 in. diameter strand. However, the ultimate stress results were lower than expected for the 0.5 in. diameter super strands. In the two grade 300 sets of strands, no test made it to strength while in one of the two sets of grade 270 strands only one strand made it to strength. A definite problem exists in super strands.
- The ultimate elongations were well beyond the required elongations for all strands tested.

5.2.2 Large Block Pullout Tests

- The LBPT results were above the suggested minimum of 36 kips (Logan 1997). All of the strands also had transfer and development lengths lower than the predicted values from ACI 318-05. Therefore, the benchmark of 36 kips for 0.5 in. diameter regular strand was conservative for this research.
- The 0.5 in. diameter super strands had pullout strengths at or near the proposed minimum of 39 kips and had transfer and development lengths below the predicted values, which indicates that this is a conservative limit for these strands.

- The 0.6 in. diameter strands tested had an average pullout strength above the proposed limit of 51 kips and had transfer and development lengths significantly below the predicted values. Once again, 51 kips was a conservative threshold for this strand.
- The pullout strengths for grade 300 strand were slightly higher than that of grade 270 strand indicating that the bond of grade 300 strand is similar to that of the current industry standard—grade 270 strand.
- The pullout strengths for two reels of grade 270 0.5 in. diameter super strand received at different times from the same manufacturer had significantly different pullout values indicating that the surface condition of strand may vary in strand received from the same producer.

5.2.3 NASP Tests

- The NASP Test Values were above the required minimum of 10.5 kips for 0.5 in. diameter regular strand and 12.6 kips for 0.6 in. diameter strand. As previously mentioned, the transfer and development lengths were below the predicted values indicating that the two minimums were conservative for the strands used in this research.
- The NASP Test Values for one of the sets of 0.5 in. diameter super strands was below the proposed minimum of 11.5 kips. However, the transfer and development lengths for all of the super strands were below the predicted values, which indicates that the limit of 11.5 kips is conservative for the 0.5 in. diameter super strands used.
- No discernible difference was evident between the pullout strengths of grade 300 and grade 270 prestressing strand.

- Similar to the LBPT’s, the two reels of grade 270 0.5 in. diameter super strand had different pullout strengths which indicates that the surface condition of strand may vary in strand from the same manufacturer.
- It was difficult to meet the requirements for the grout mix.

5.3 Recommendations for Further Research

Little research has been done on the material properties of grade 300 strand or on the material properties of 0.5 in. diameter super strand. The research as part of this thesis indicated that grade 300 strand may have a higher modulus of elasticity than grade 270 strand. More research is needed to determine if the elastic modulus is changed due to the composition changes used to achieve the higher strength. The research done for this thesis also indicated that the strength of 0.5 in. diameter super strand may be inadequate. More research should be done to determine if the ultimate stress for super strand is below the guaranteed ultimate stress.

Currently, the LBPT procedure indicates that for concrete compressive strengths between 3500 and 5900 psi there is little change in the pullout strength. Research is needed to determine the effects of different concrete strengths on the results of Large Block Pullout Tests. Also, the transfer and development lengths for all of the strands were significantly below the predicted values. However, the pullout strengths for some strands in both pullout tests were near the minimum allowed values. Research is needed to determine if the current benchmarks could be lowered and still be conservative.

Both the LBPT and the NASP Bond Test use the same benchmark value for 0.5 in. diameter regular and super strands despite the super strand having a 9 percent larger area. Research should be done to determine if a separate minimum pullout strength is needed for 0.5 in. diameter super strand. Finally, a minimum pullout strength for the LBPT has not been determined for 0.6 in. diameter strand. Research is needed to determine a conservative minimum so that the surface condition of 0.6 in. diameter strand can be evaluated by the same means as smaller strands.

The NASP Test can be difficult to perform due to the grout mix. A parametric study is needed to determine the effect of grout strength, grout flow, and curing times on the results of the NASP Test. If the restrictions could be relaxed the test could be easier to perform and therefore a better standard test for the evaluation of strand surface condition.

For many strands the force applied during the LBPT's was higher than the force at which the strand broke during the tension tests. Due to notching from the prestressing chuck, the strand should fail well before its breaking strength. Research is needed to determine how higher strengths could be obtained during a LBPT than during a tension test.

REFERENCES

American Association of State and Highway Transportation Officials (AASHTO). (2006). *AASHTO LRFD Bridge Design Specifications*, Third Edition, Washington, D.C.

American Concrete Institute (ACI). (2005). *Building Code Requirements for Structural Concrete and Commentary*, Committee 318, Farmington Hills, MI.

ASTM A370-05. (2005). "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," American Society for Testing and Materials, West Conshohocken, PA.

ASTM A416-05/A416M-05. (2005). "Standard Specification for Steel Strand, Uncoated Seven-wire for Prestressed Concrete," American Society for Testing and Materials, West Conshohocken, PA.

Brearley, L.M. Jr. and Johnston, D.W. (1990) "Pull-out Bond Tests of Epoxy-Coated Prestressing Strands," *Journal of Structural Engineering*, 116(8), 2236-2252.

Cousins, T.E. (1985). "Bond of Epoxy Coated Prestressing Strand," Ph.D. Dissertation, North Carolina State University, Raleigh, NC, December 1986.

Devalapura, R.K. and Tadros, M.K. (1992). "Stress-Strain Modeling of 270 ksi Low-Relaxation Prestressing Strands," *PCI Journal*, 37(2), 100-105.

Godfrey, H.J. (1956). "The Physical Properties and Methods of Testing Prestressed Concrete Wire Strand," *PCI Journal*, 1(3), 38-47.

Hill, A.T. Jr. (2006). "Material Properties of Grade 300 and Grade 270 Prestressing Strands and Their Impact on the Design of Bridges," M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, April 2006.

Hodges, H.T. (2006). "Top Strand Effect and Evaluation of Effective Prestress in Prestressed Concrete Beams," M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, December 2006.

Logan, D.R. (1997). "Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications," *PCI Journal*, 42(2), 52-90.

Mote, J. (2001). "Bond Mechanics of Steel Prestressing Strand," M.S. Thesis, University of Oklahoma, Norman, OK, July 2001.

Nilson, A.H. (1987). *Design of Prestressed Concrete*, Second Edition, John Wiley & Sons, New York.

Podolney, W. Jr. (1967). "Understanding the Steel in Prestressing," *PCI Journal*, 12(3), 54-64.

Preston, H.K. (1985). "Testing 7-Wire Strand for Prestressed Concrete—The State of the Art," *PCI Journal*, 30(3), 134-155.

Preston, H.K. (1990). "Handling Prestressed Concrete Strand," *PCI Journal*, 35(6), 68-71.

Ramirez, J.A and Russell, B.W. (2007). "Transfer, Development, and Splice Length for Strand/Reinforcement in High-Strength Concrete," *Draft Final Report NCHRP 12-60*, Purdue University, School of Civil Engineering, West Lafayette, IN.

Rose, D.R. and Russel, B.W. (1997). "Investigation of Standardized Tests to Measure the Bond Performance of Prestressing Strand," *PCI Journal*, 42(4), 56-80.

A. APPENDIX A: STRESS-STRAIN CURVES FOR TENSION TESTS

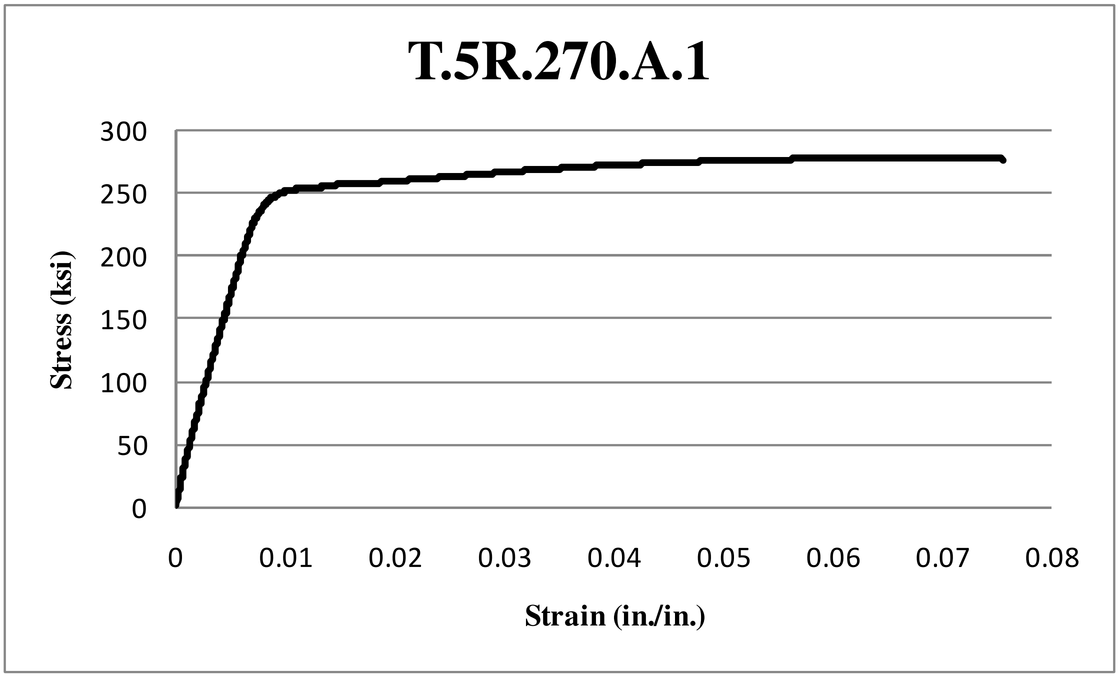

Figure A.1 Stress-Stain Curve for T.5R.270.A.1

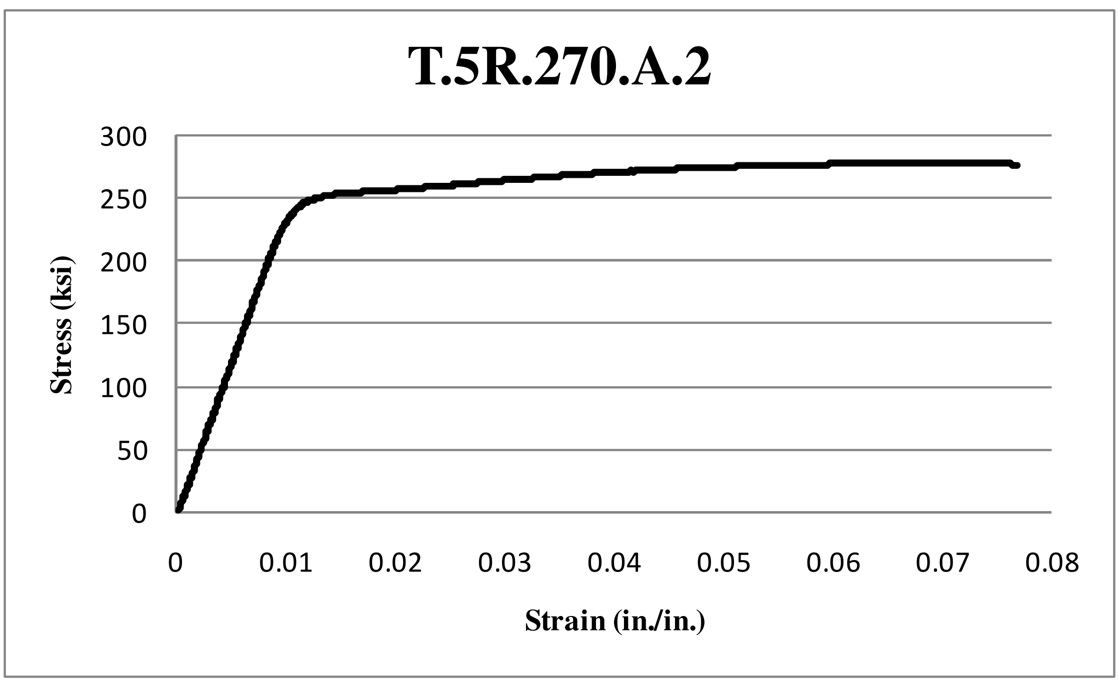

Figure A.2 Stress-Strain Curve for T.5R.270.A.2

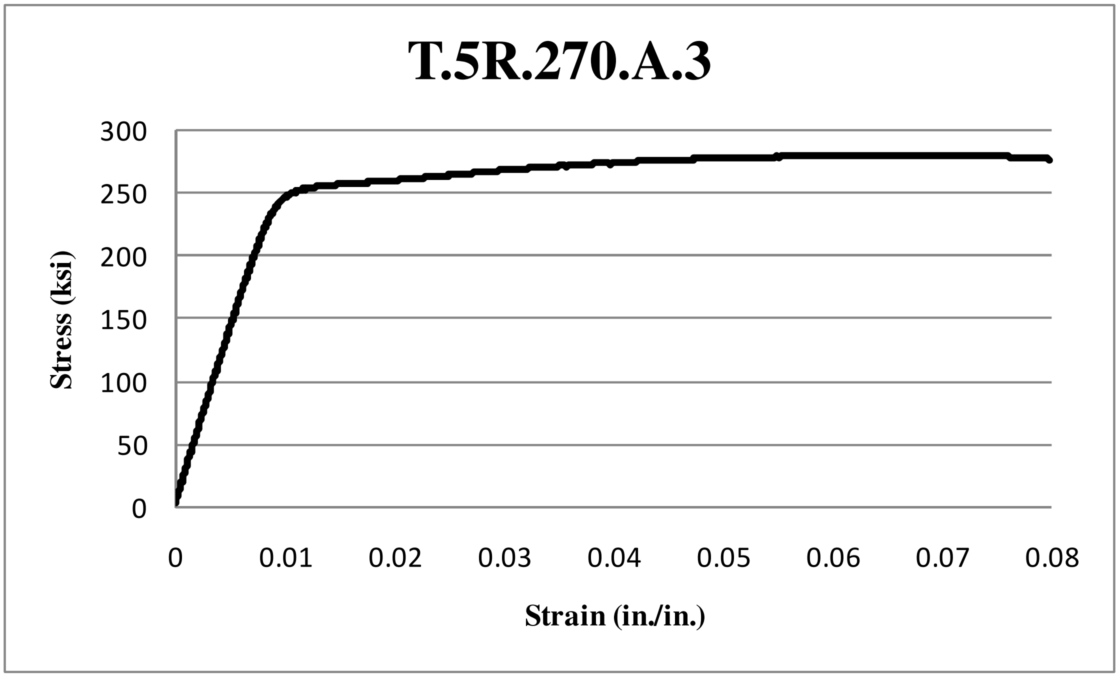

Figure A.3 Stress-Strain Curve for T.5R.270.A.3

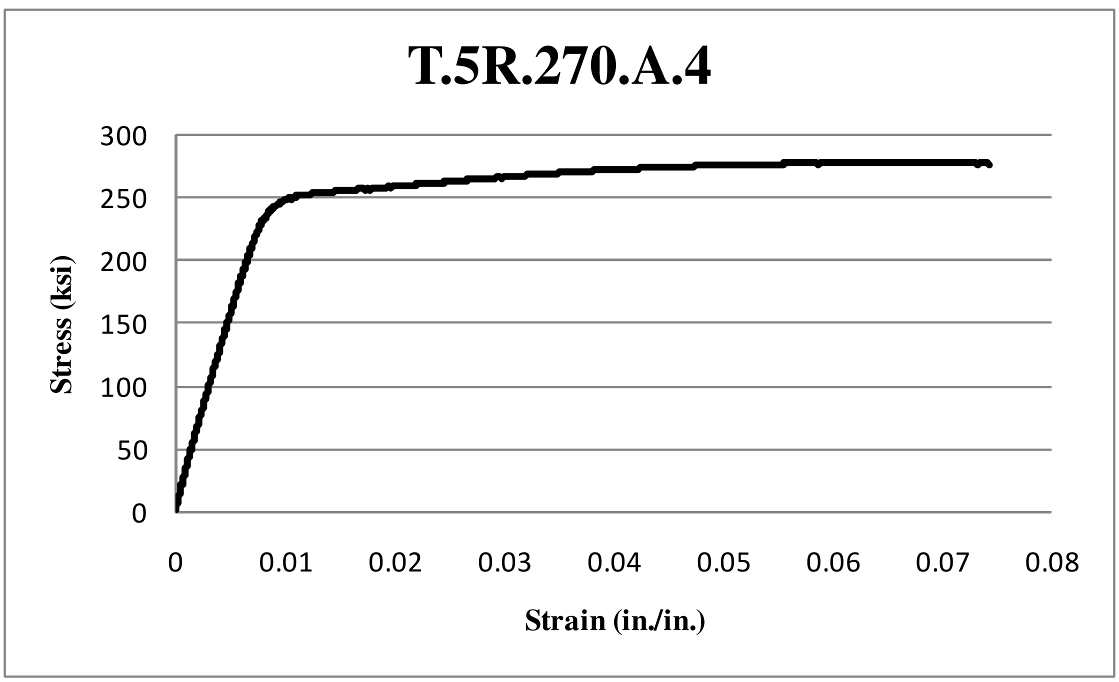

Figure A.4 Stress-Strain Curve for T.5R.270.A.4

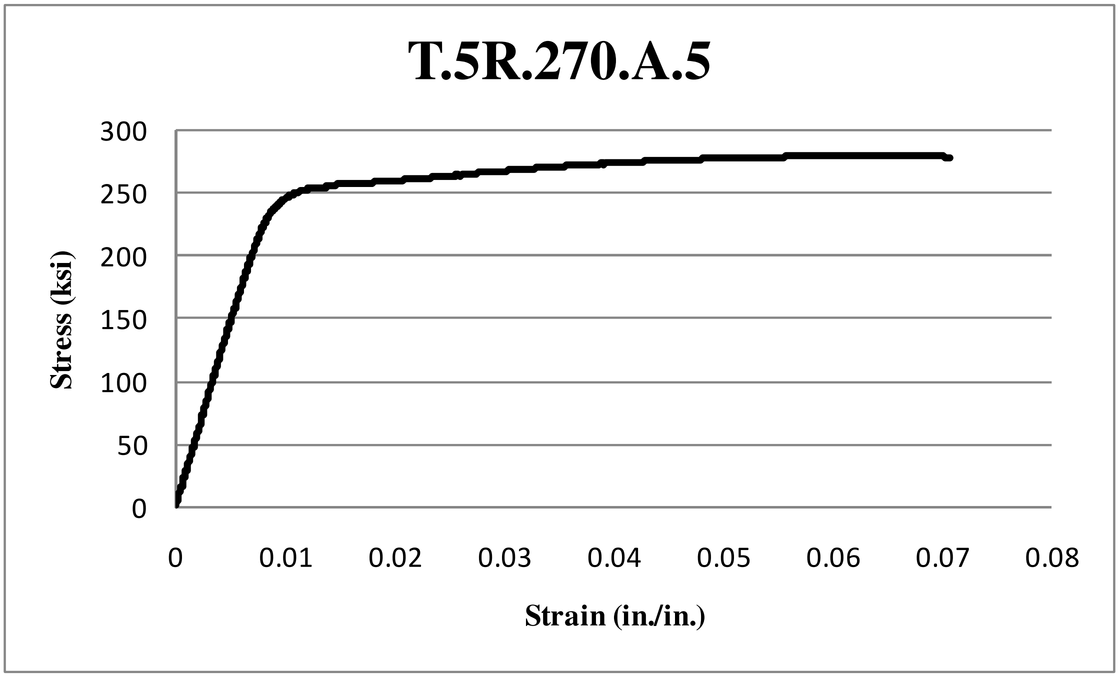

Figure A.5 Stress-Strain Curve for T.5R.270.A.5

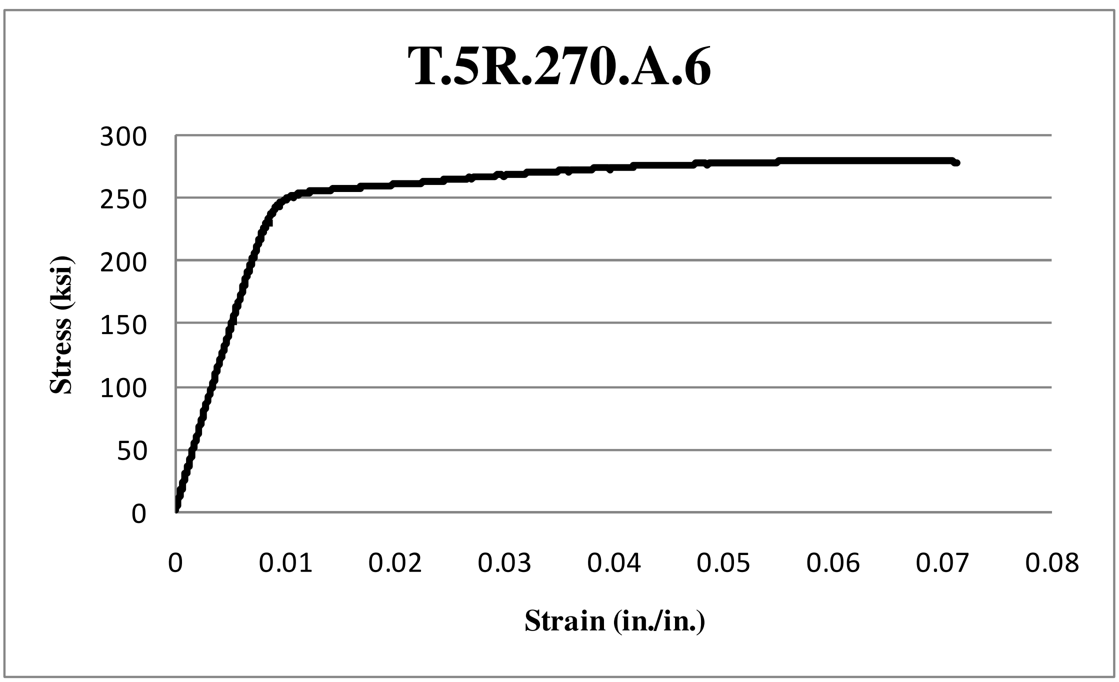

Figure A.6 Stress-Strain Curve for T.5R.270.A.6

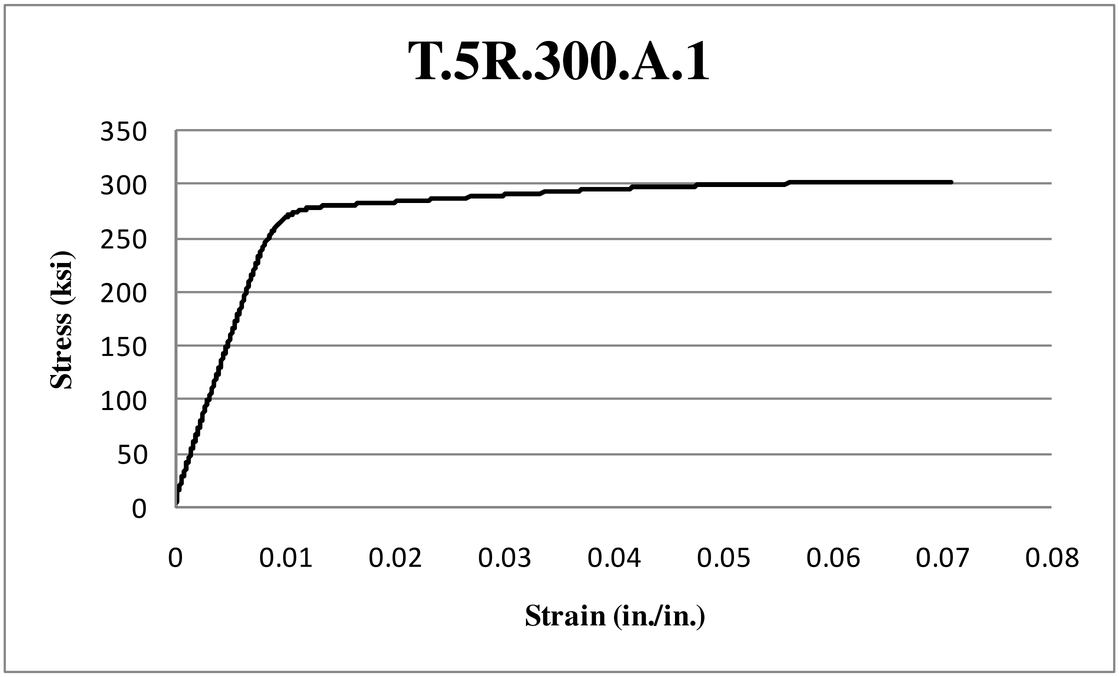

Figure A.7 Stress-Strain Curve for T.5R.300.A.1

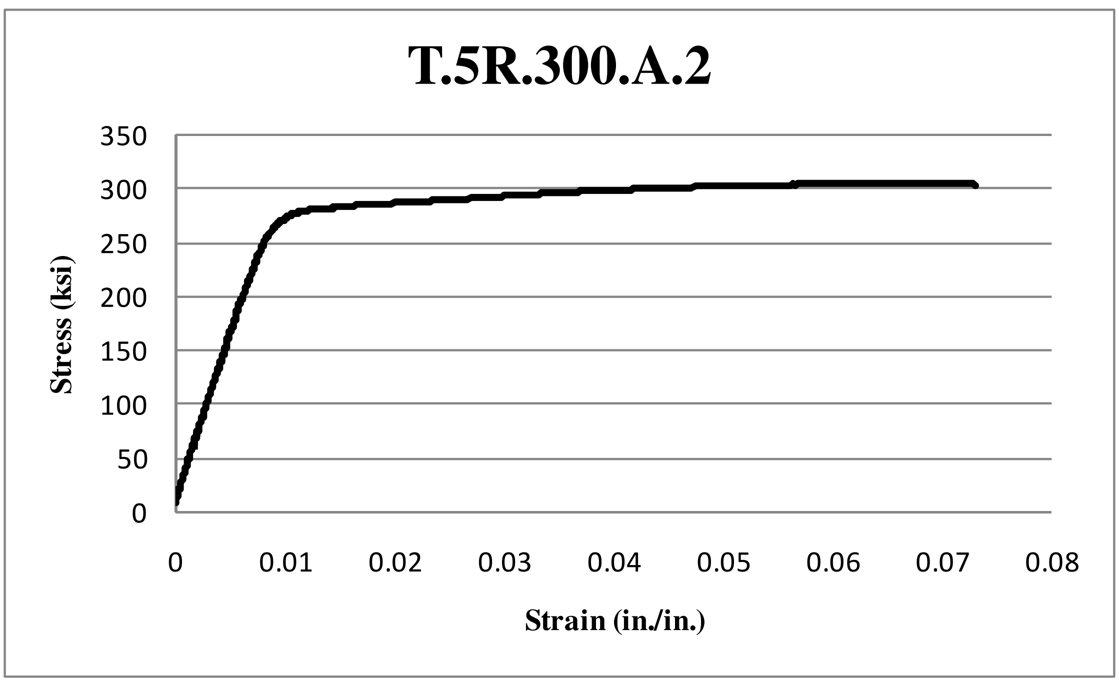

Figure A.8 Stress-Strain Curve for T.5R.300.A.2

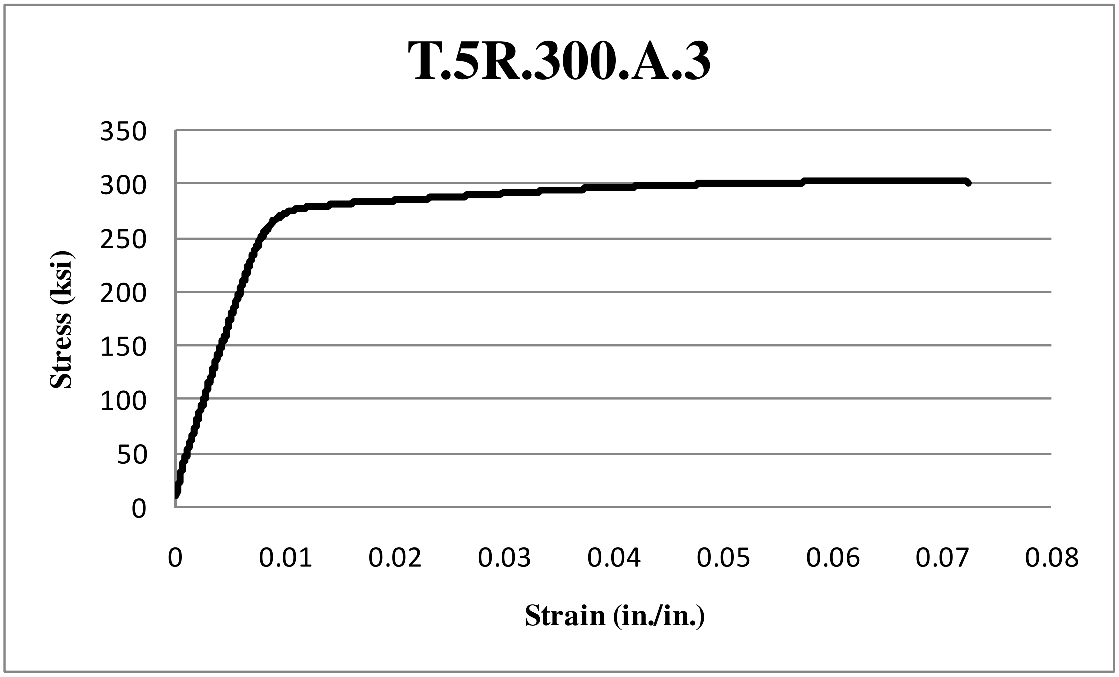

Figure A.9 Stress-Strain Curve for T.5R.300.A.3

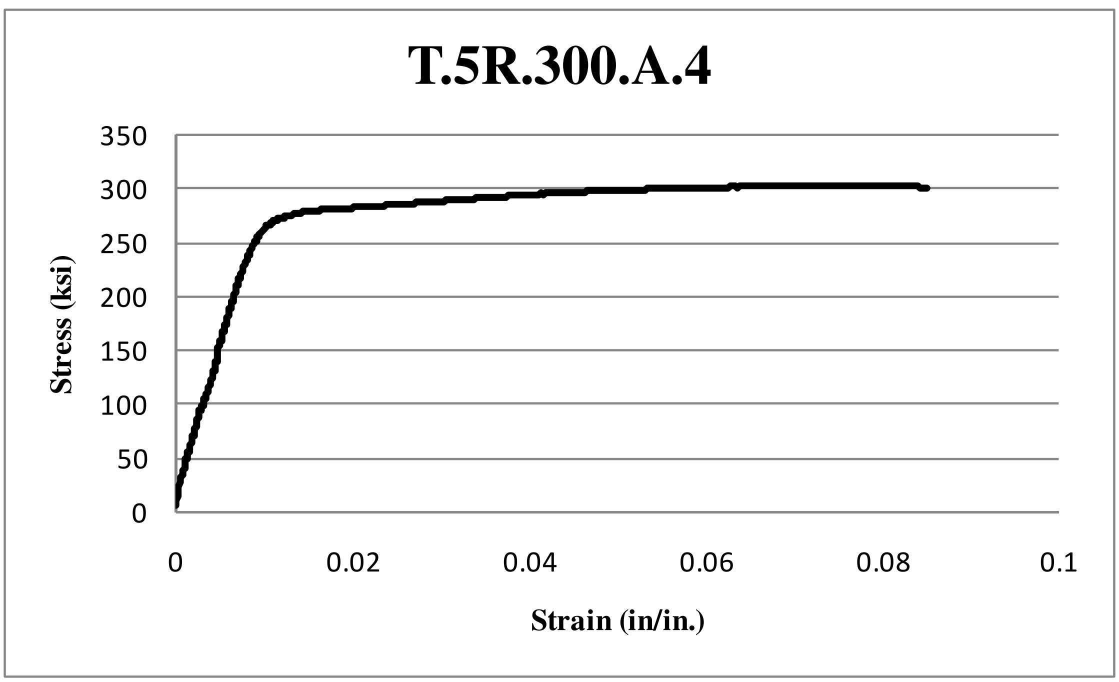

Figure A.10 Stress-Strain Curve for T.5R.300.A.4

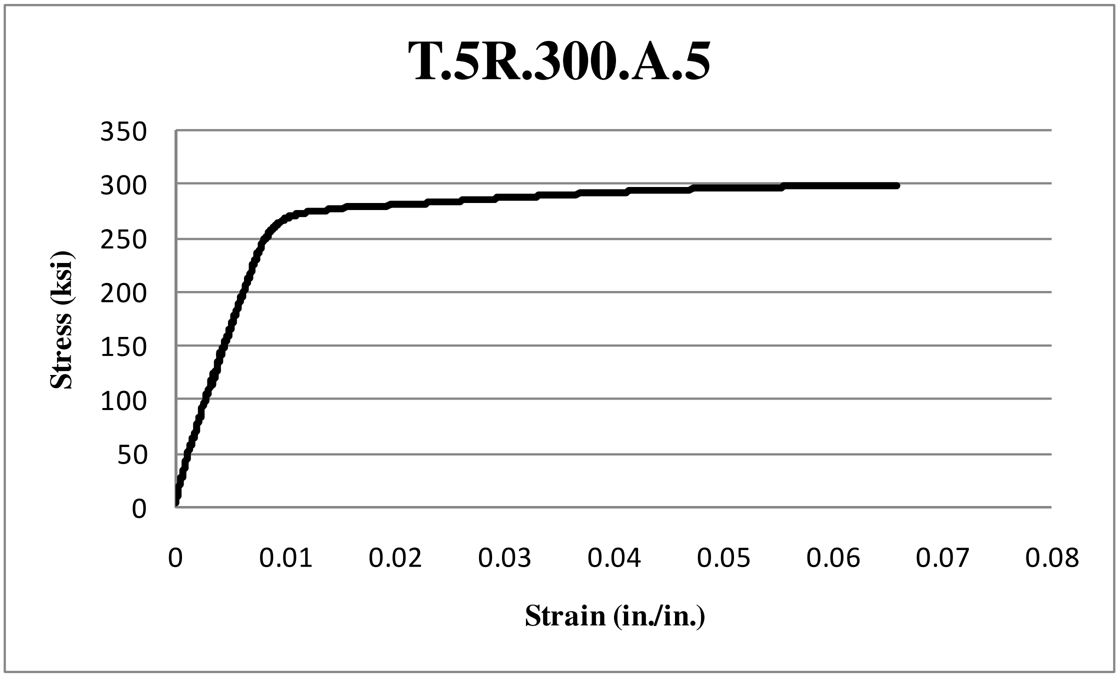

Figure A.11 Stress-Strain Curve for T.5R.300.A.5

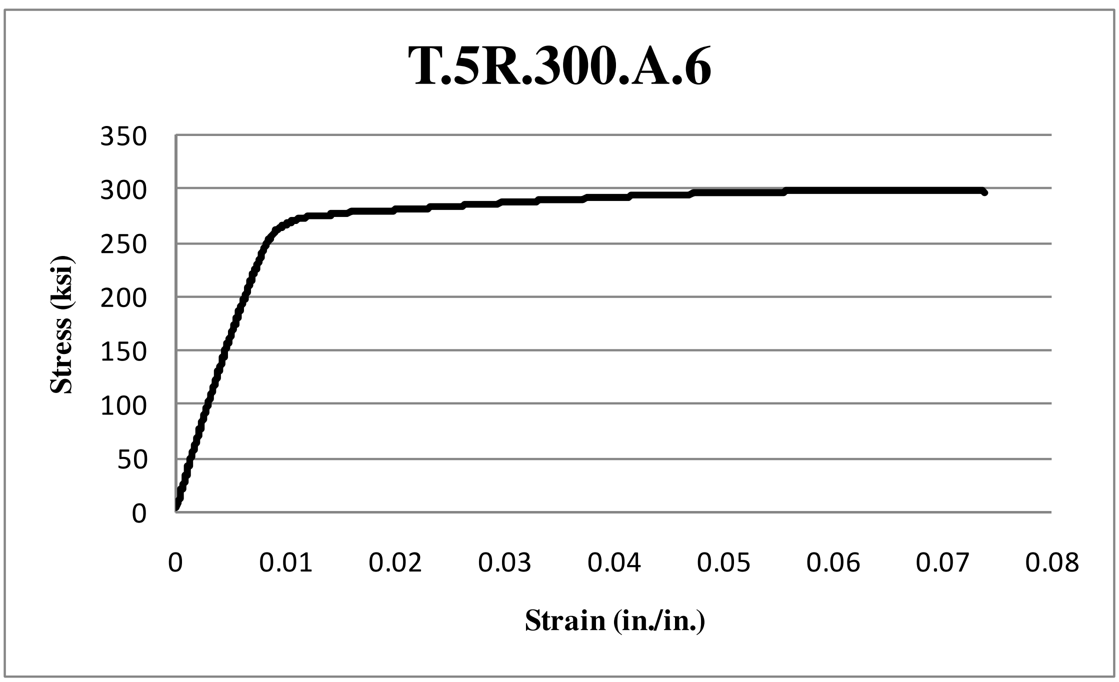

Figure A.12 Stress-Strain Curve for T.5R.300.A.6

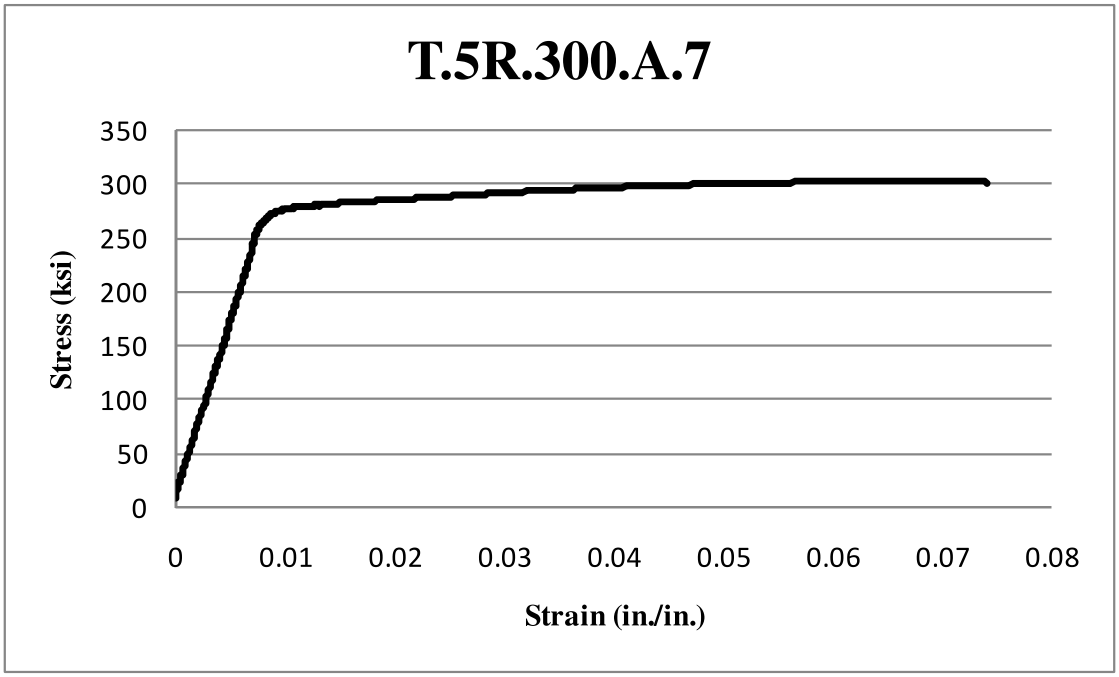

Figure A.13 Stress-Strain Curve for T.5R.300.A.7

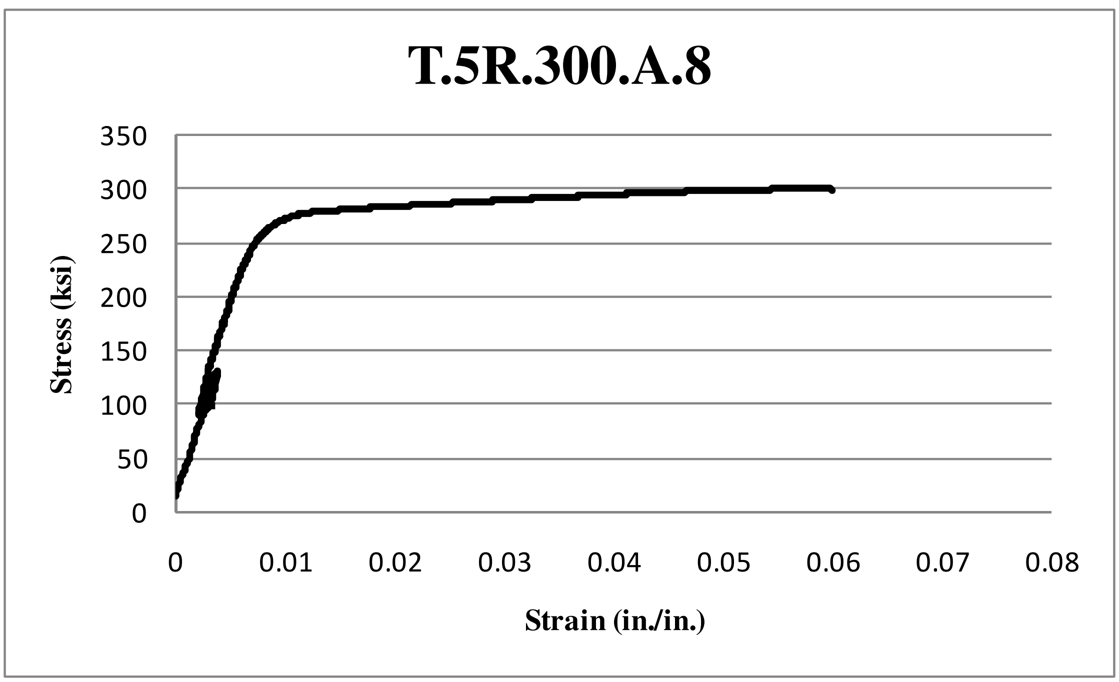

Figure A.14 Stress-Strain Curve for T.5R.300.A.8

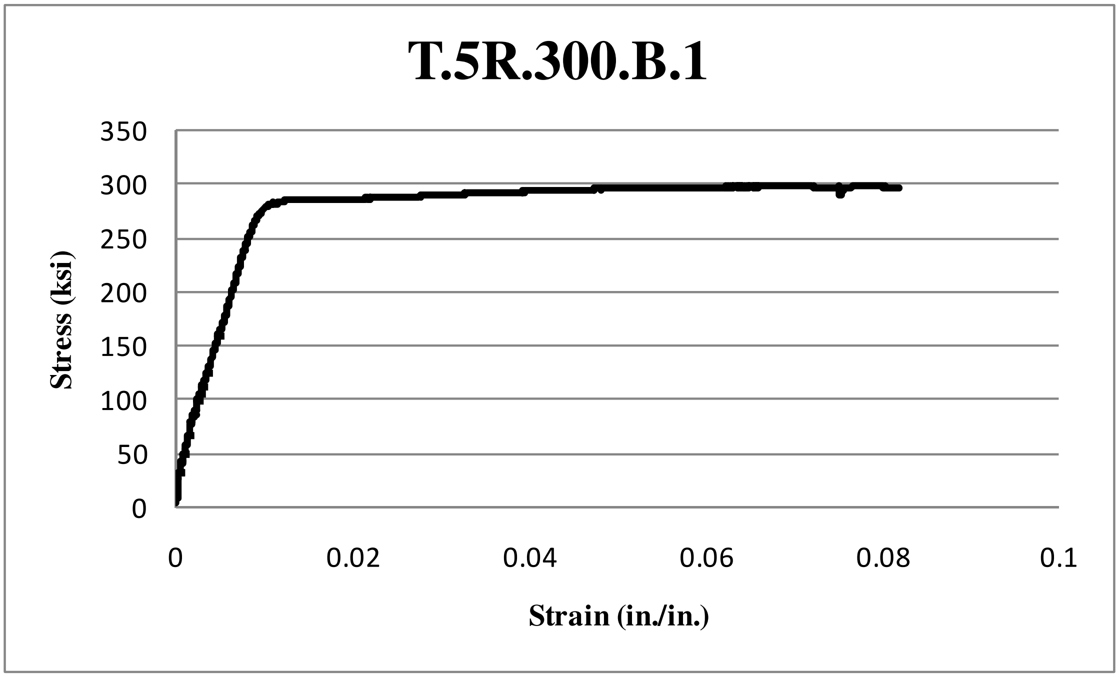

Figure A.15 Stress-Strain Curve for T.5S.300.B.1

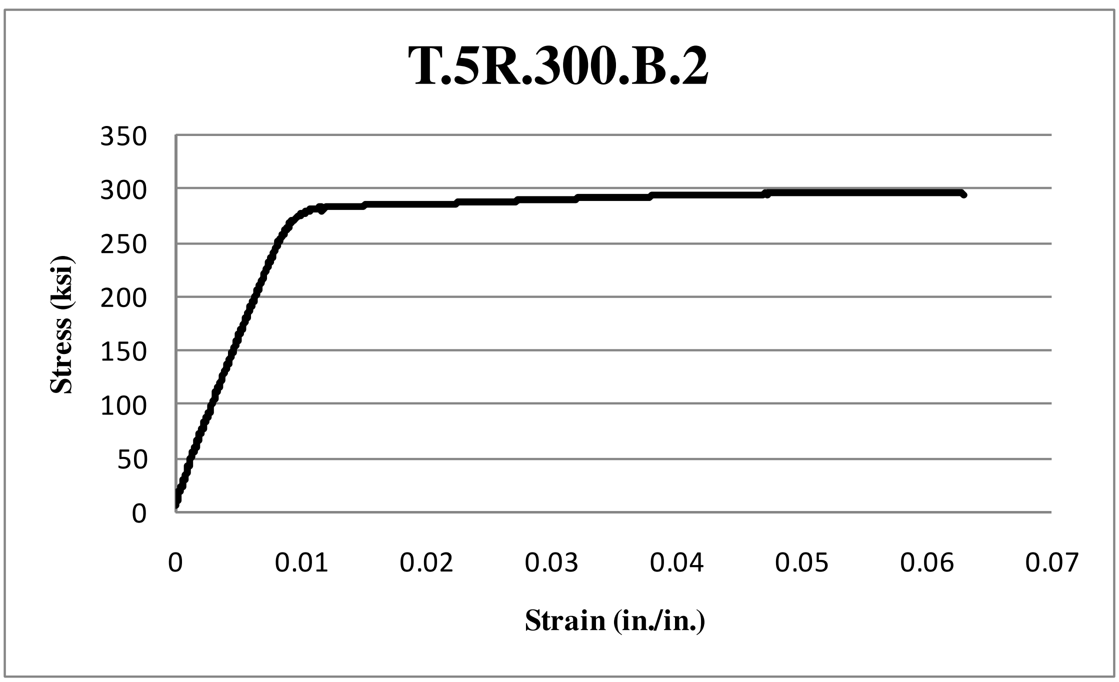

Figure A.16 Stress-Strain Curve for T.5S.300.B.2

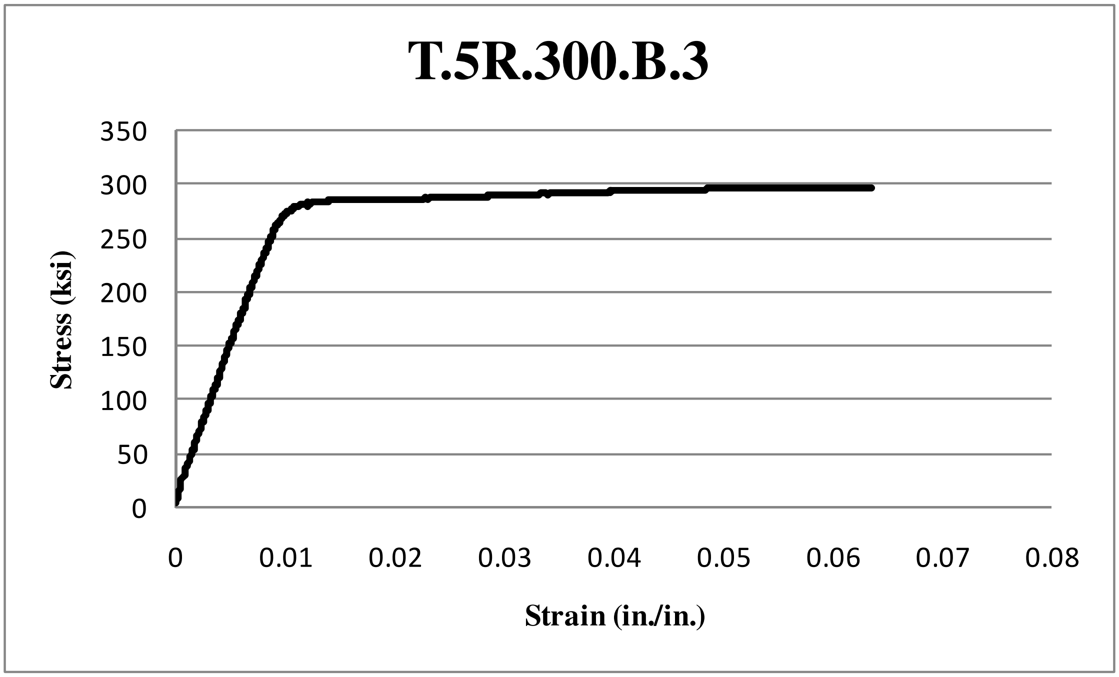

Figure A.17 Stress-Strain Curve for T.5S.300.B.3

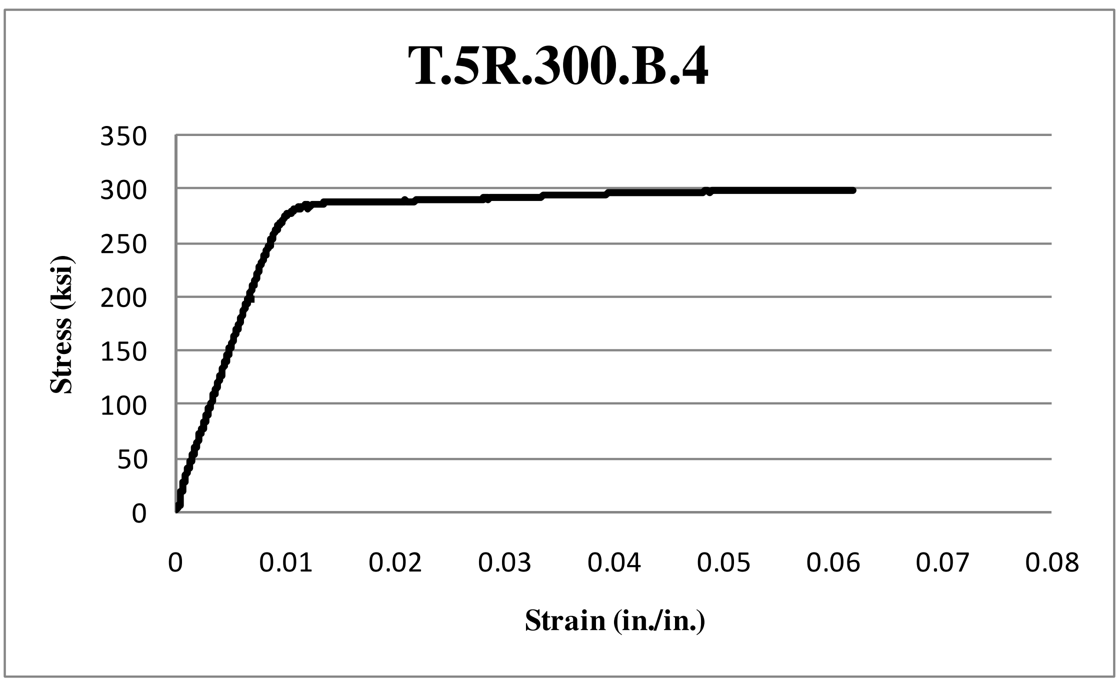

Figure A.18 Stress-Strain Curve for T.5S.300.B.4

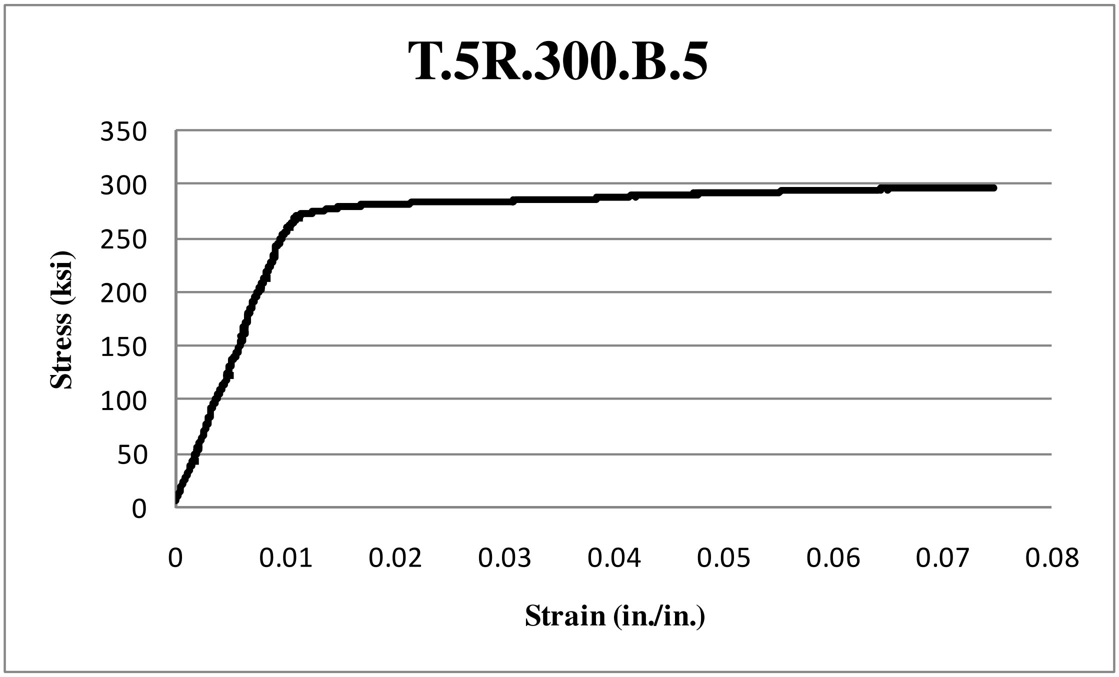

Figure A.19 Stress-Strain Curve for T.5S.300.B.5

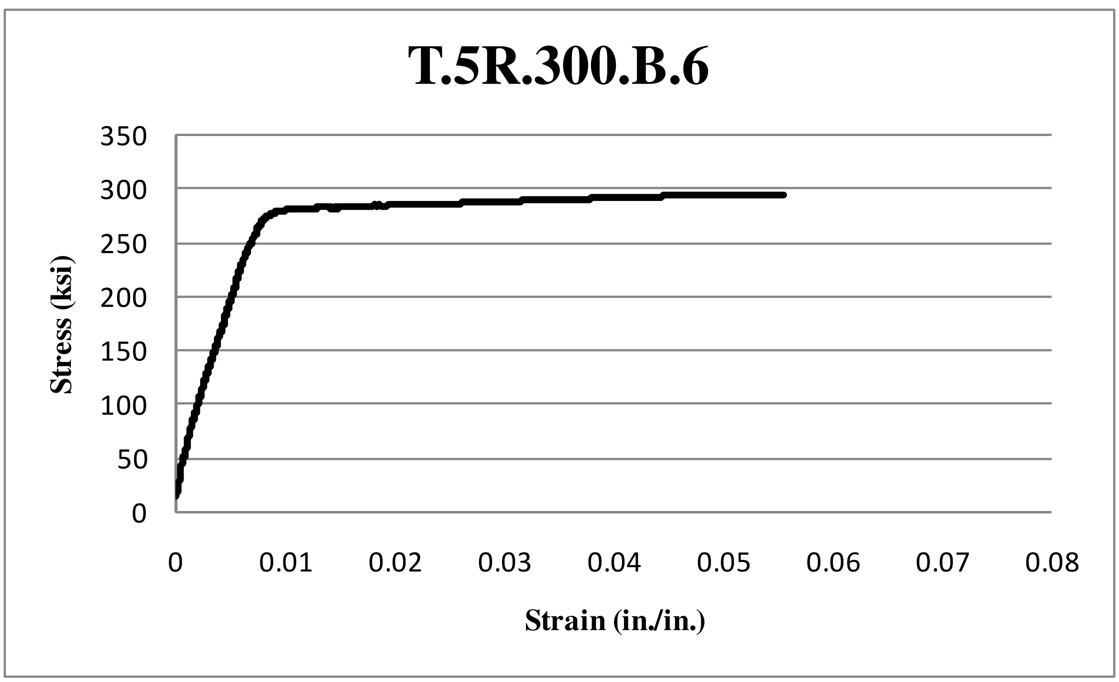

Figure A.20 Stress-Strain Curve for T.5S.300.B.6

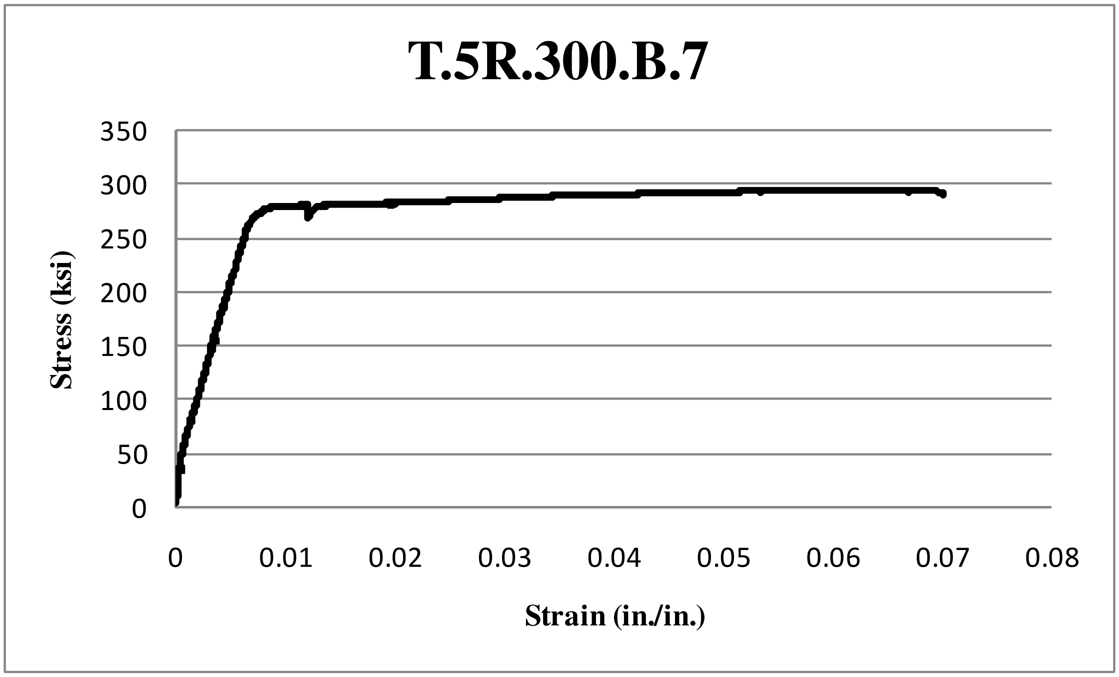

Figure A.21 Stress-Strain Curve for T.5S.300.B.7

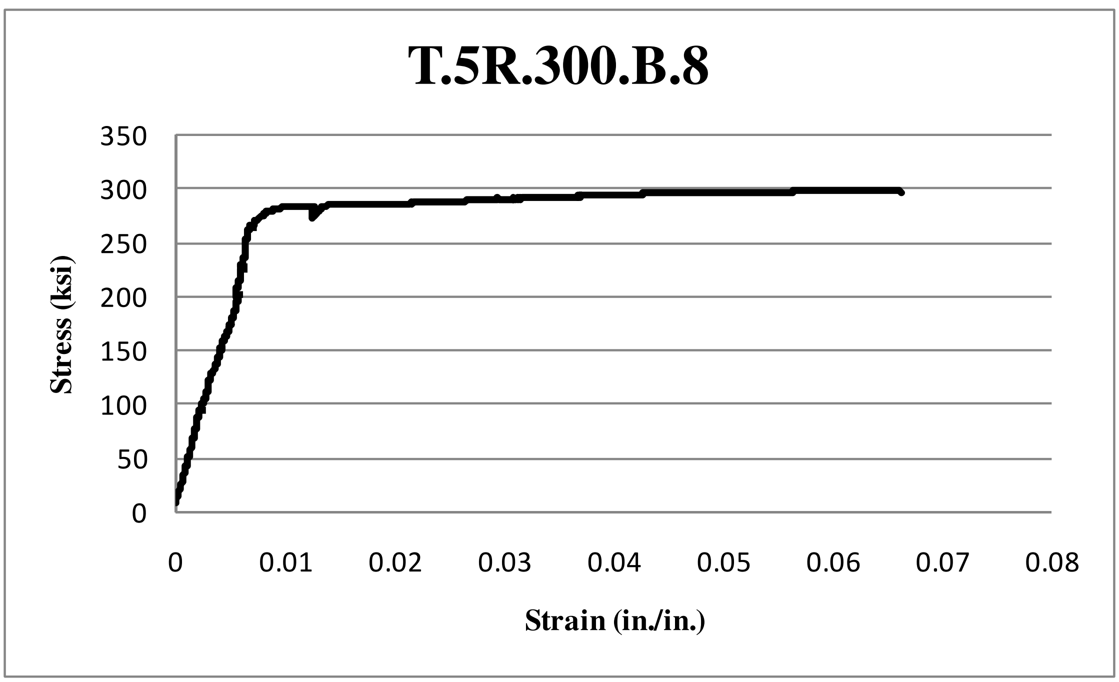

Figure A.22 Stress-Strain Curve for T.5S.300.B.8

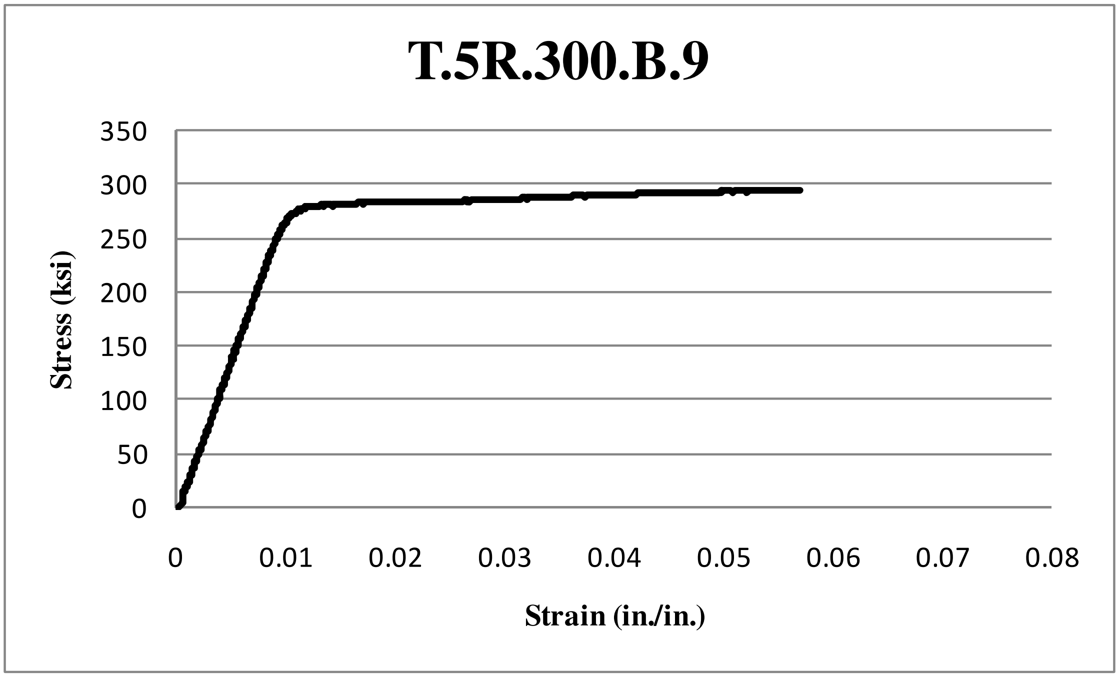

Figure A.23 Stress-Strain Curve for T.5S.300.B.9

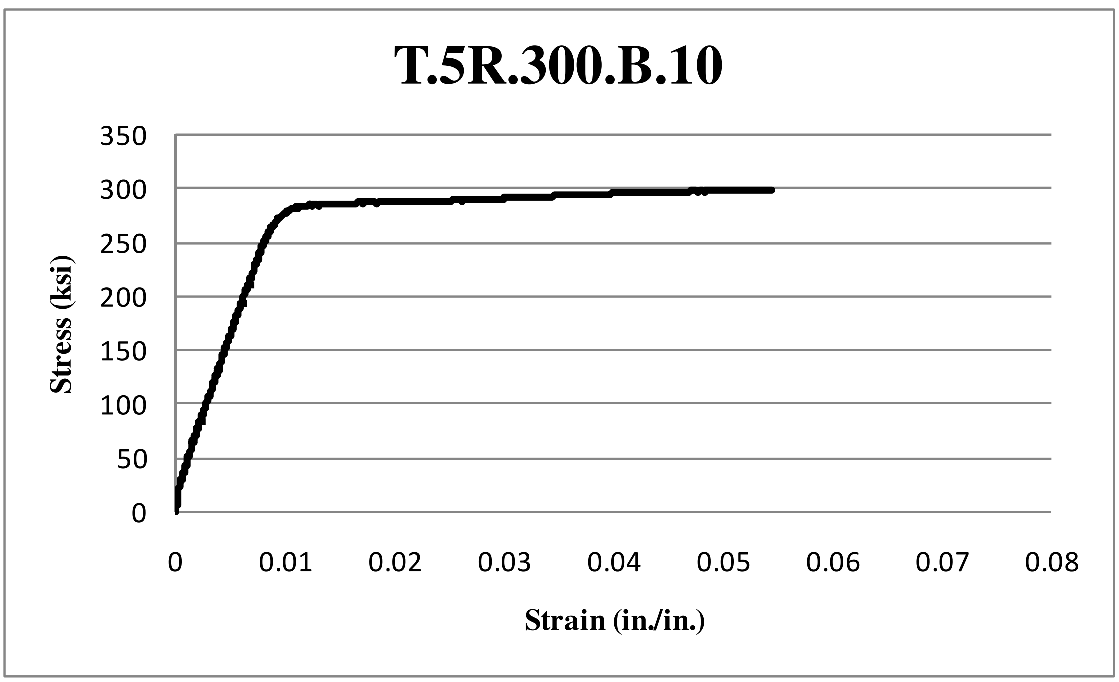

Figure A.24 Stress-Strain Curve for T.5S.300.B.10

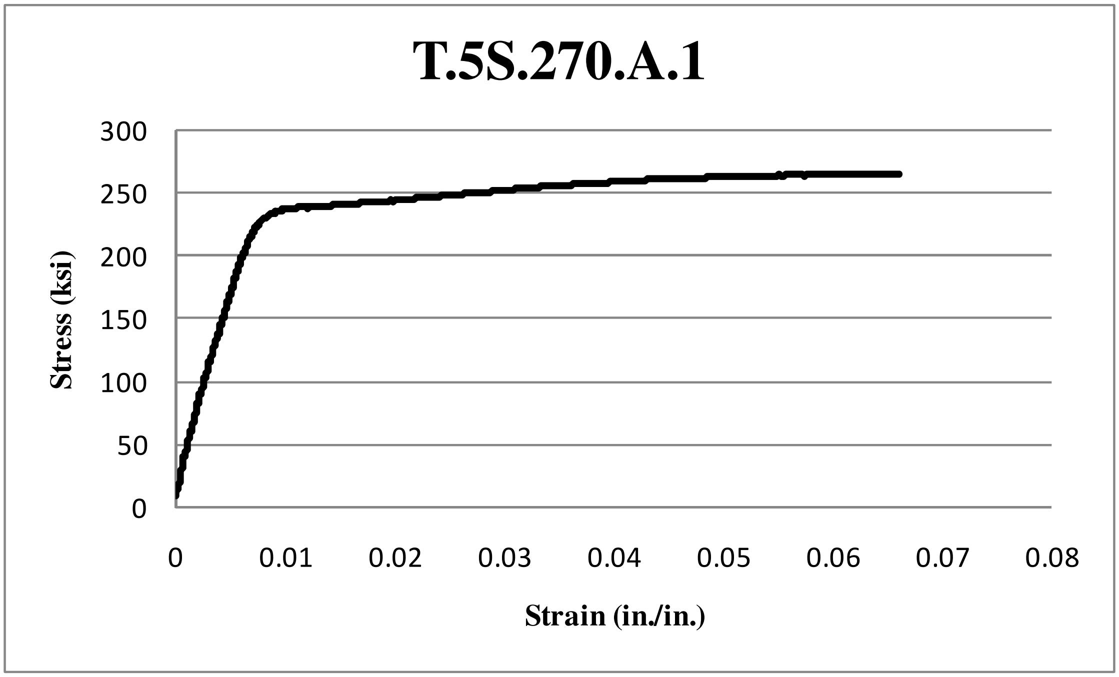

Figure A.25 Stress-Strain Curve for T.5S.270.A.1

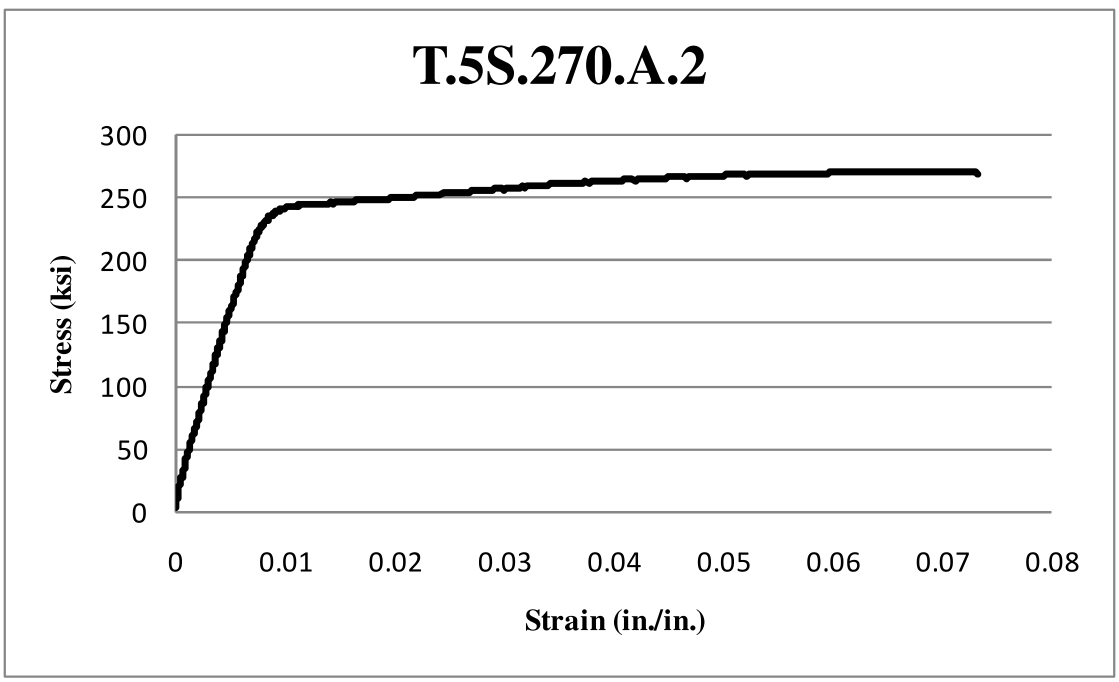

Figure A.26 Stress-Strain Curve for T.5S.270.A.2

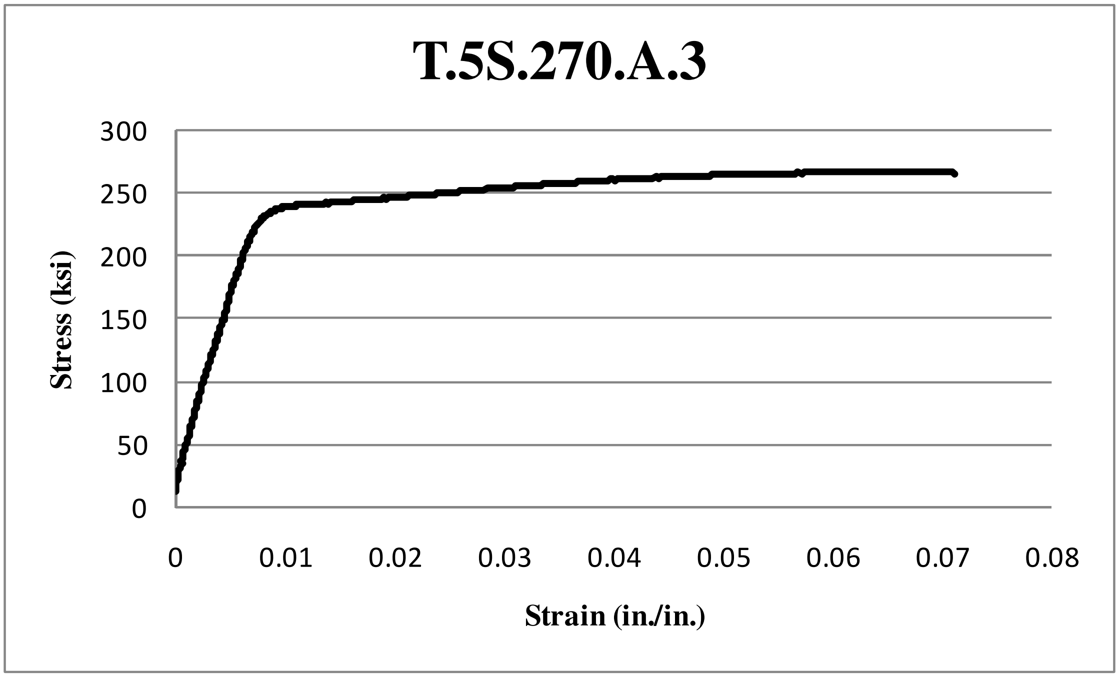

Figure A.27 Stress-Strain Curve for T.5S.270.A.3

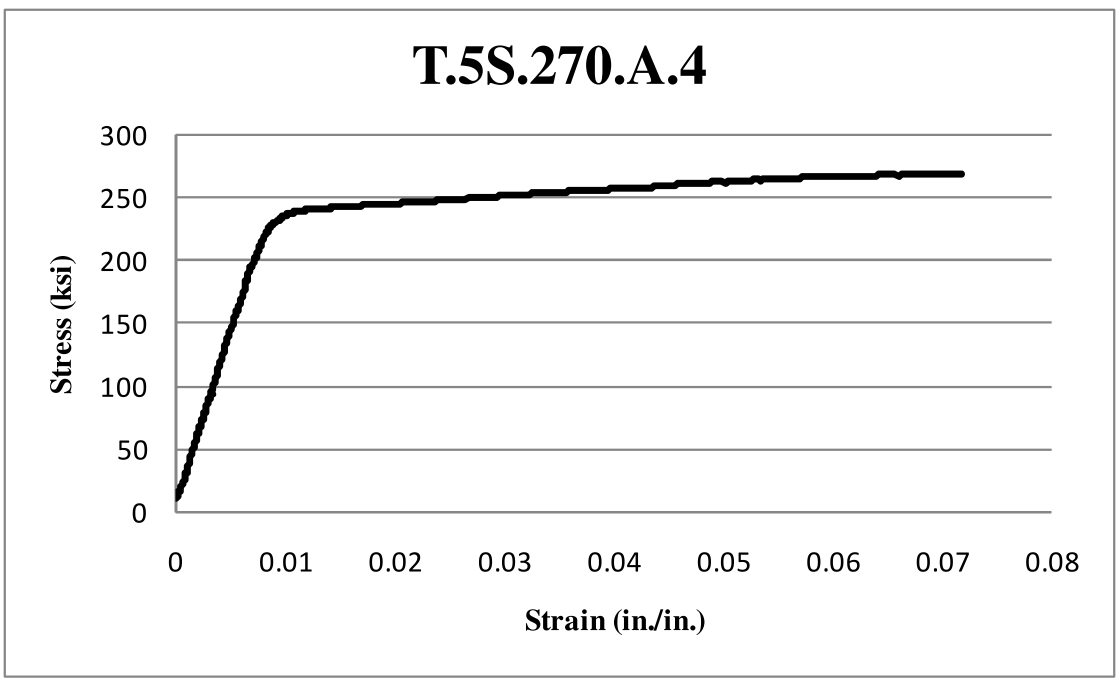

Figure A.28 Stress-Strain Curve for T.5S.270.A.4

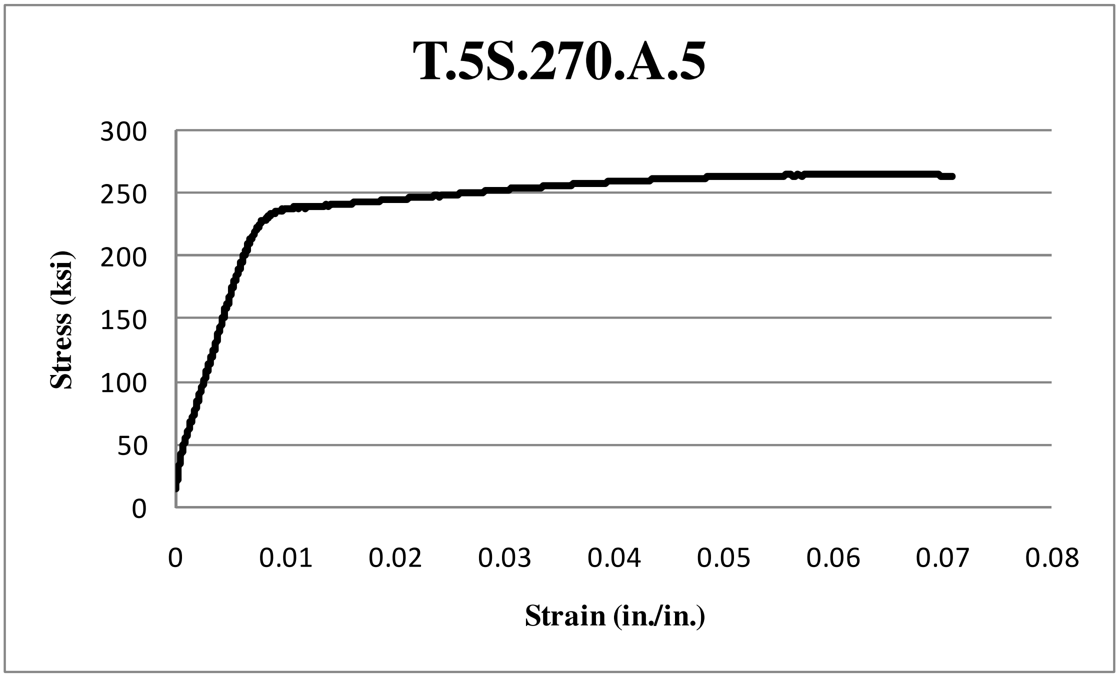

Figure A.29 Stress-Strain Curve for T.5S.270.A.5

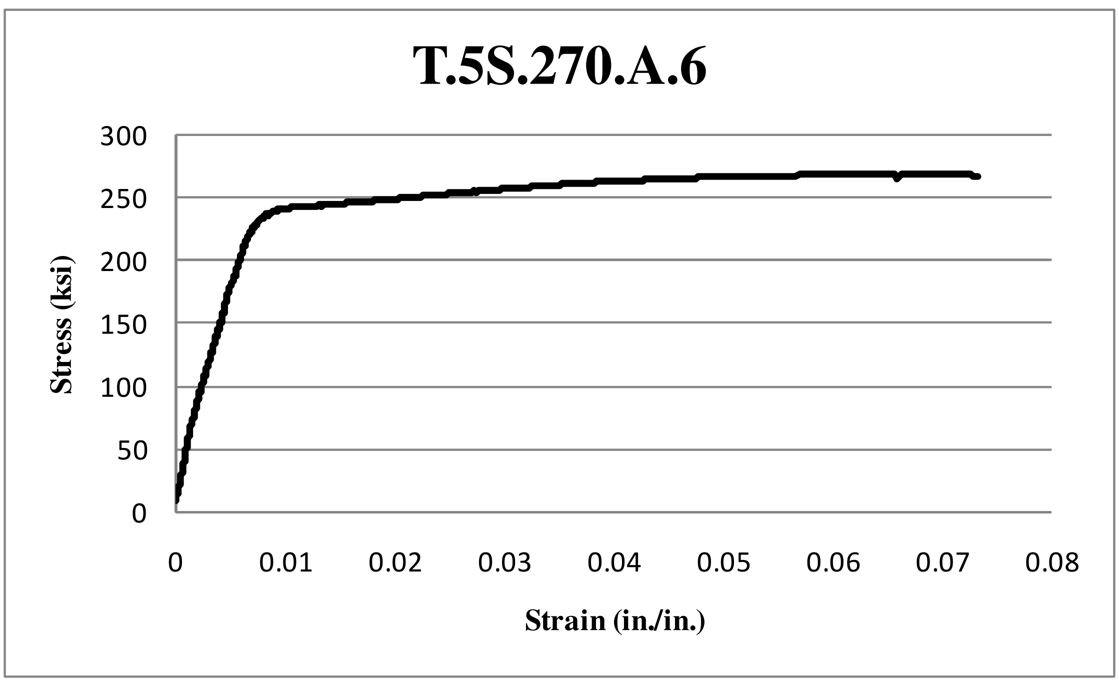

Figure A.30 Stress-Strain Curve for T.5S.270.A.6

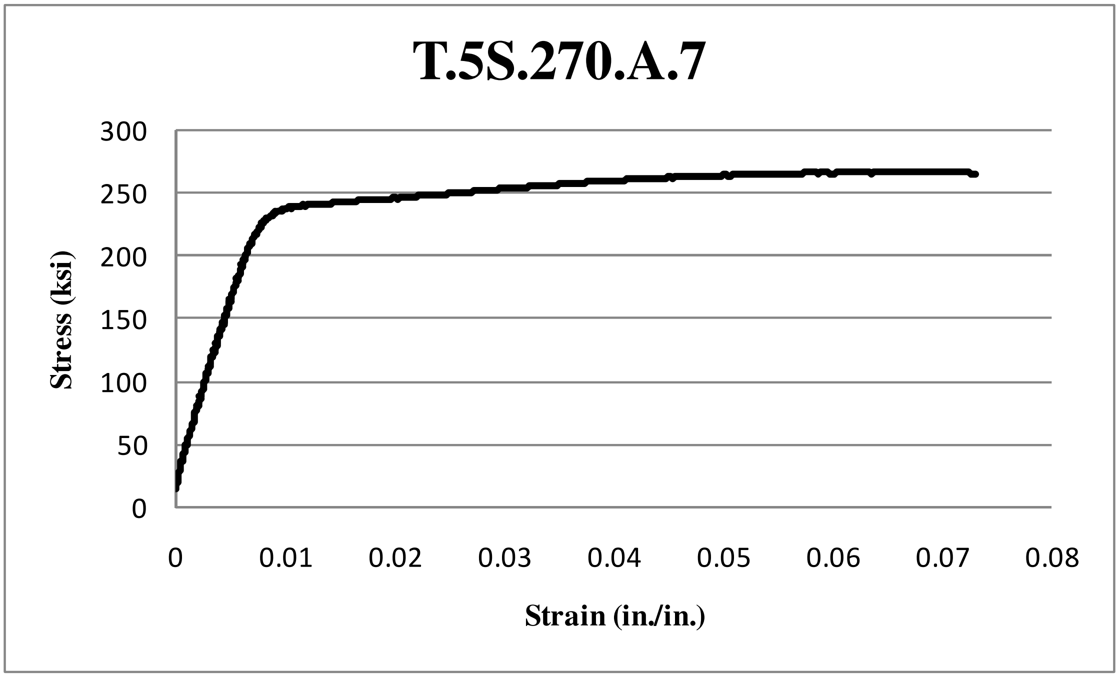

Figure A.31 Stress-Strain Curve for T.5S.270.A.7

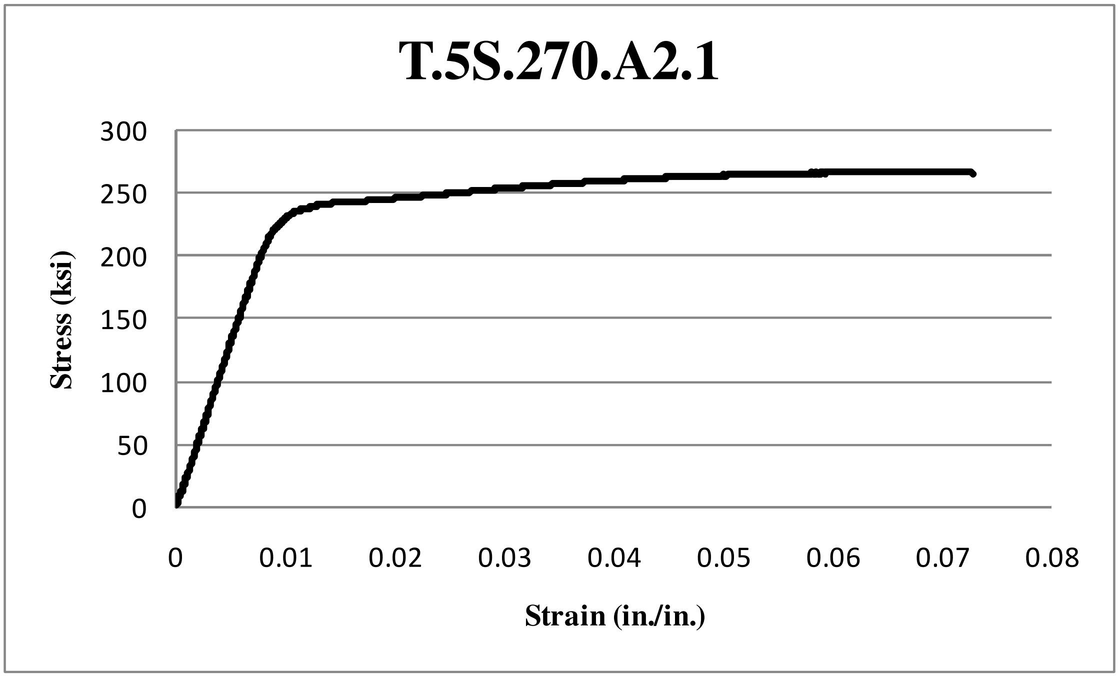

Figure A.32 Stress-Strain Curve for T.5S.270.A2.1

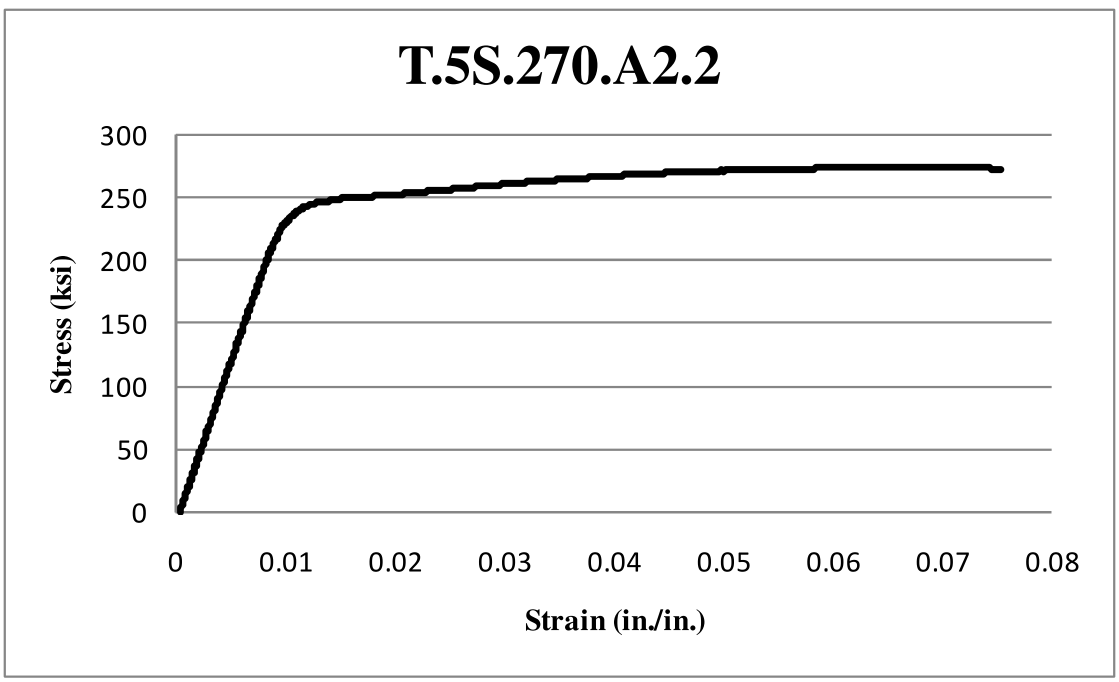

Figure A.33 Stress-Strain Curve for T.5S.270.A2.2

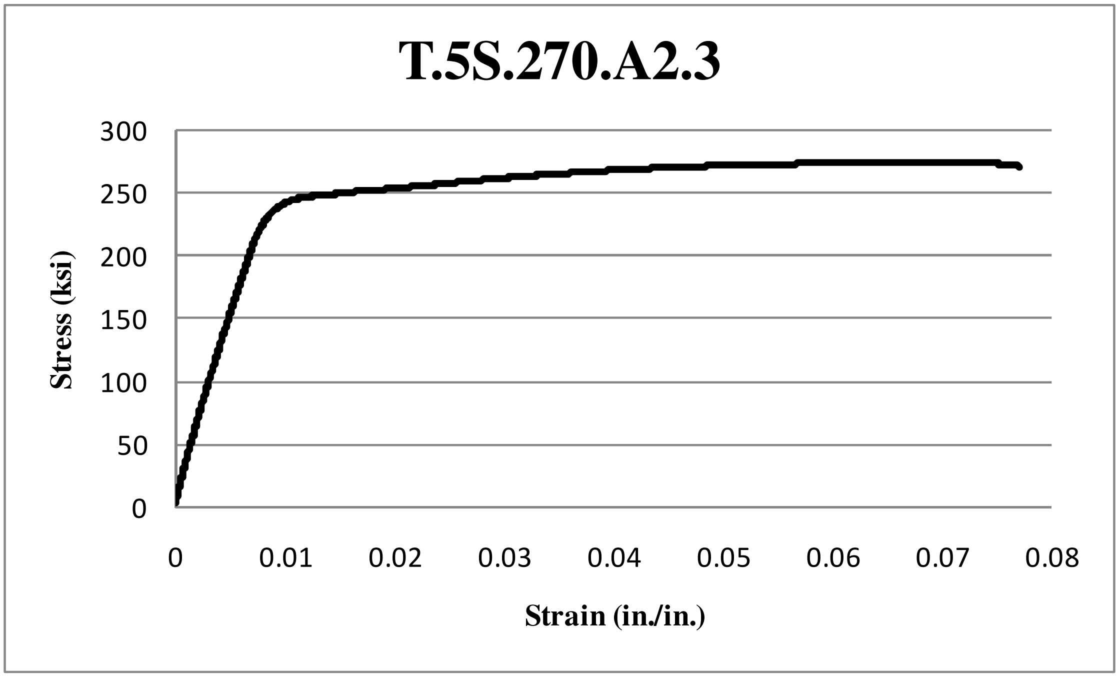

Figure A.34 Stress-Strain Curve for T.5S.270.A2.3

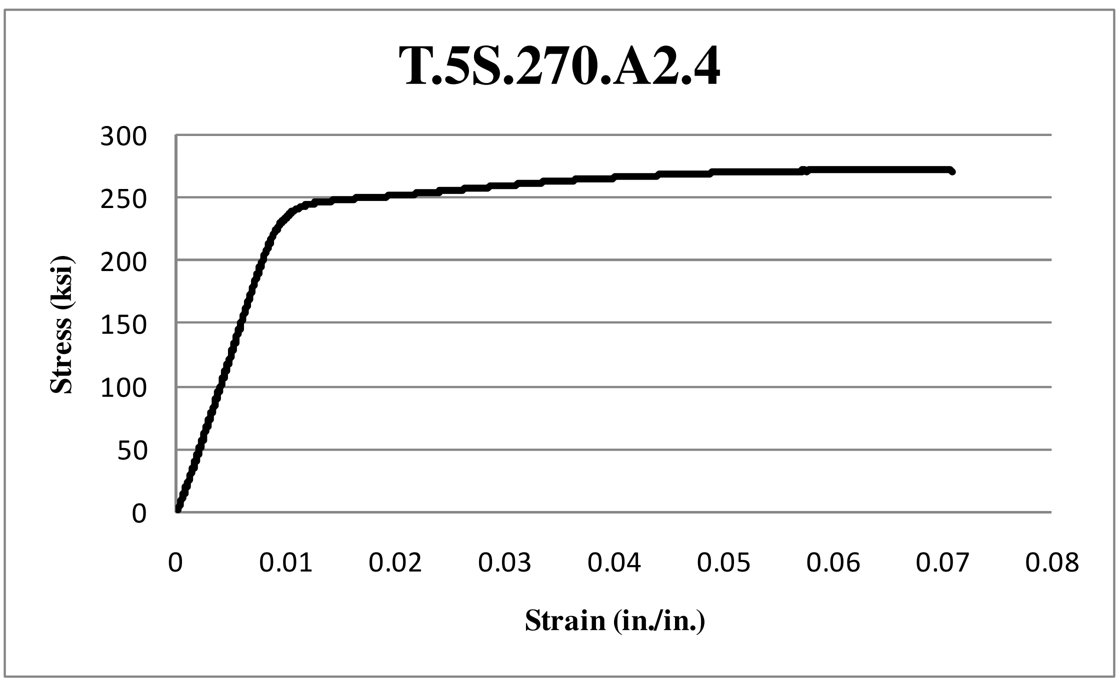

Figure A.35 Stress-Strain Curve for T.5S.270.A2.4

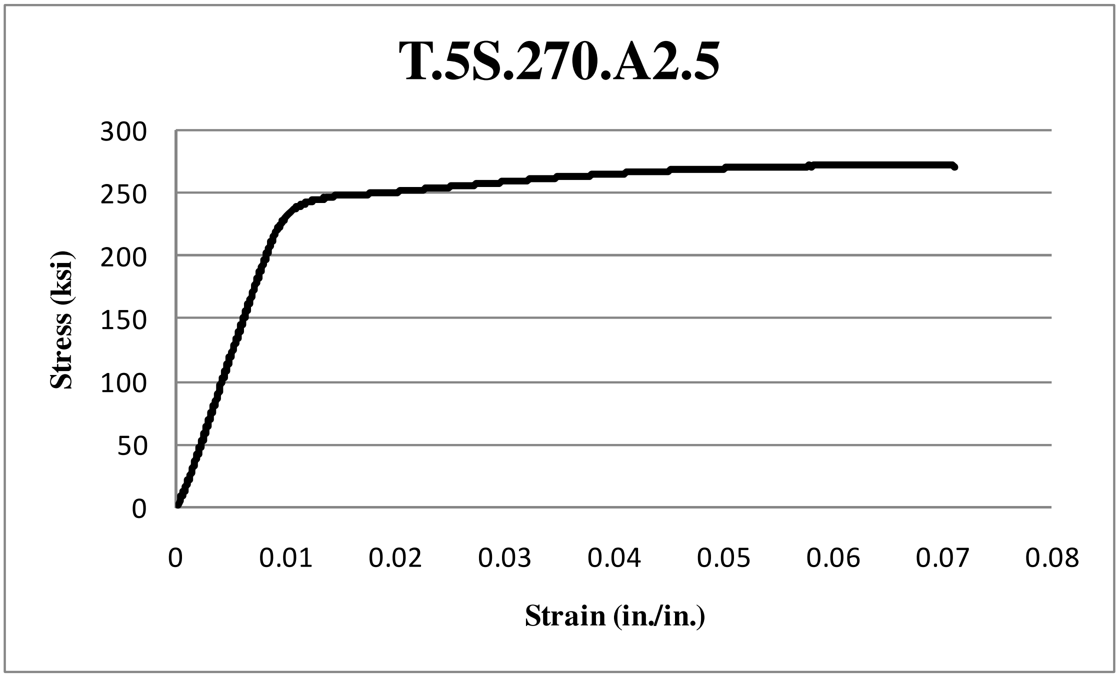

Figure A.36 Stress-Strain Curve for T.5S.270.A2.5

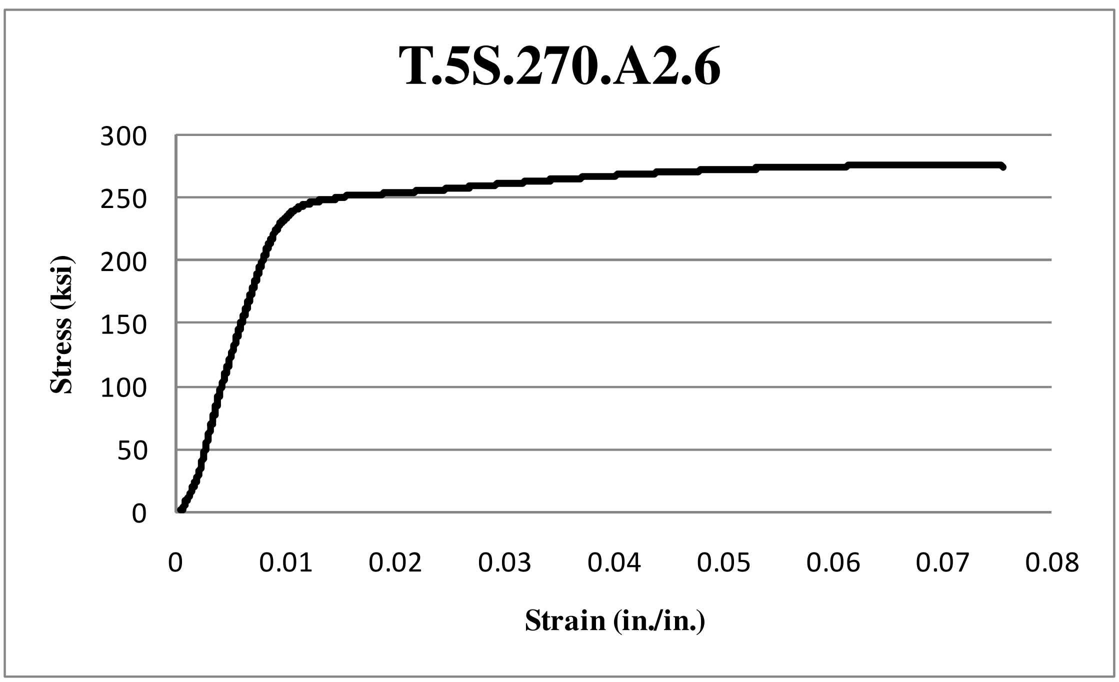

Figure A.37 Stress-Strain Curve for T.5S.270.A2.6

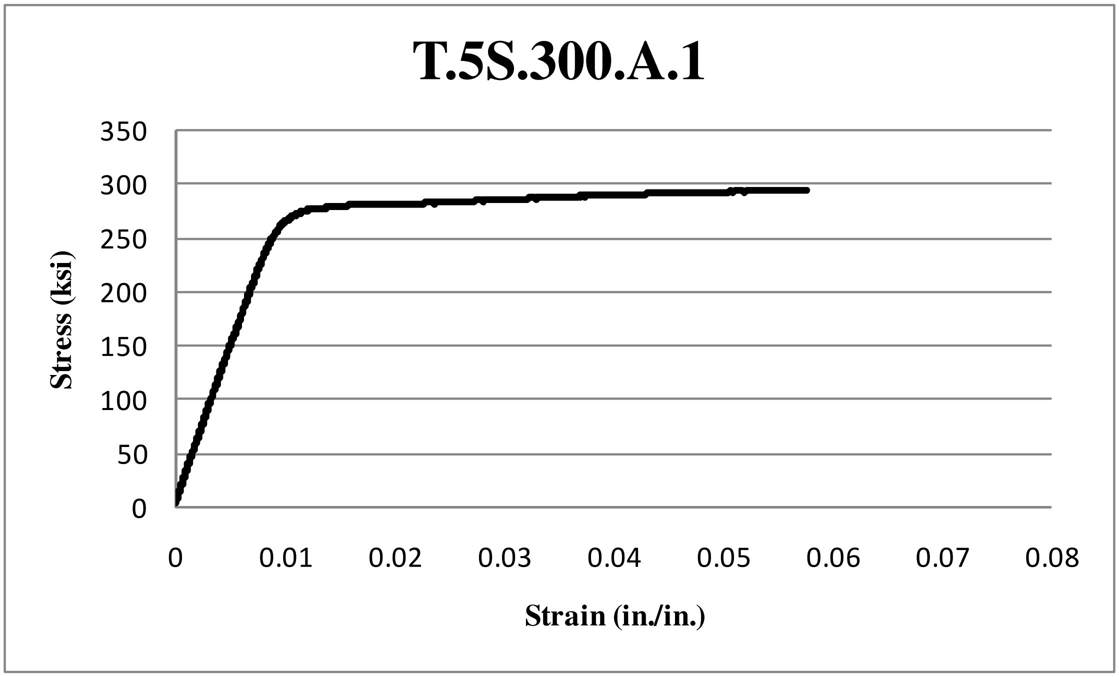

Figure A.38 Stress-Strain Curve for T.5S.300.A.1

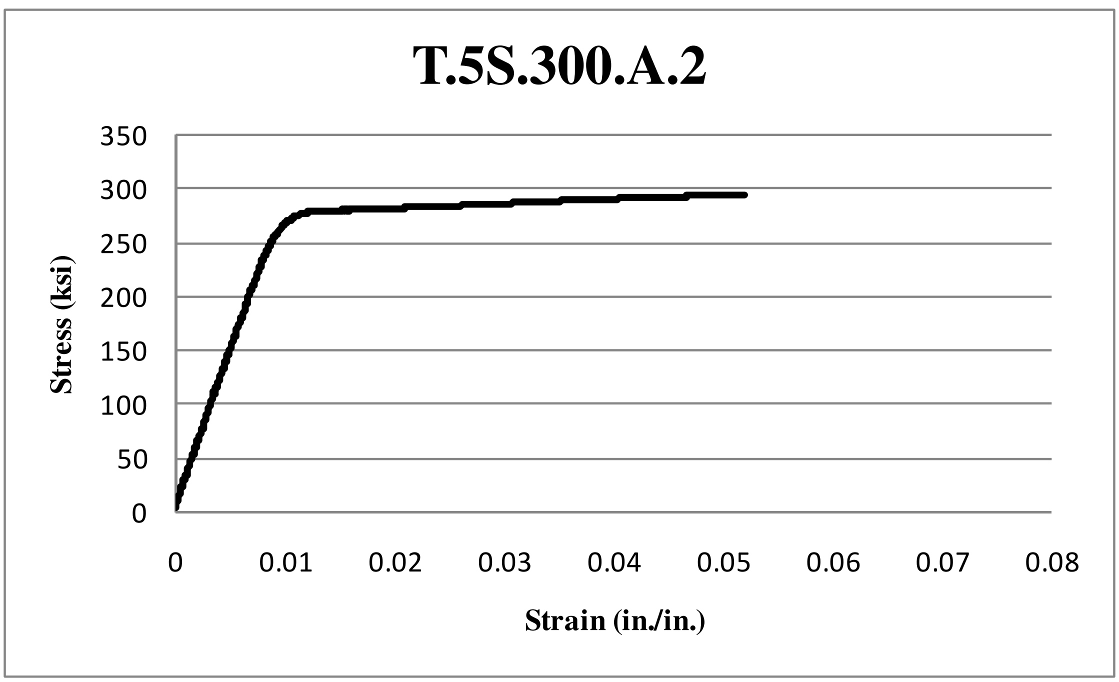

Figure A.39 Stress-Strain Curve for T.5S.300.A.2

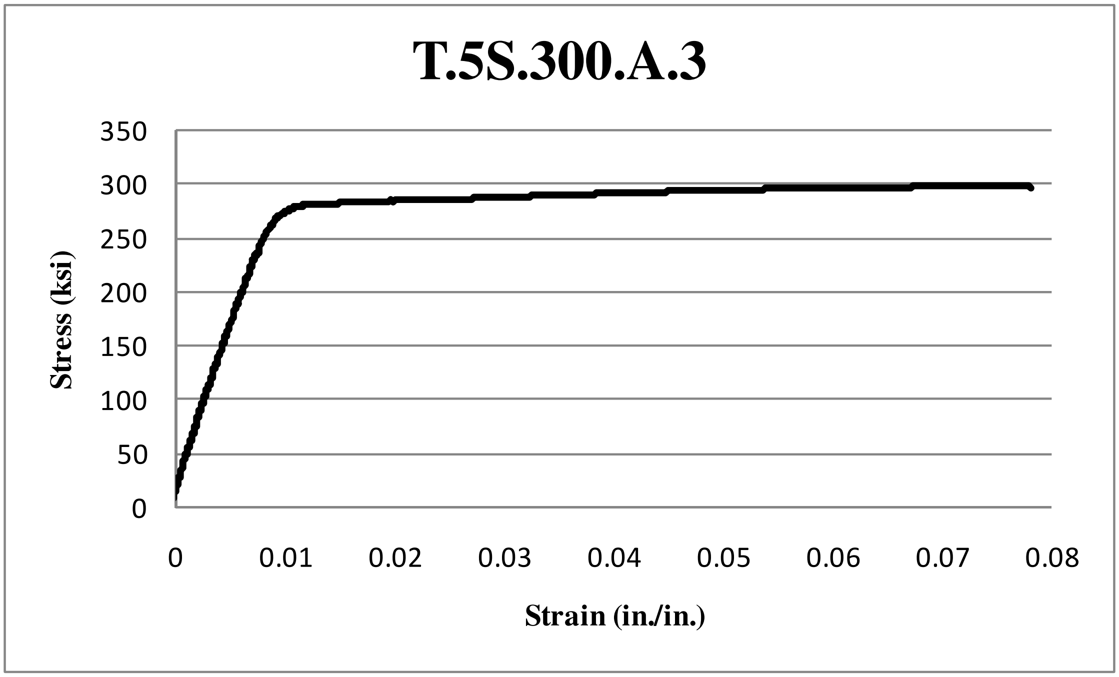

Figure A.40 Stress-Strain Curve for T.5S.300.A.3

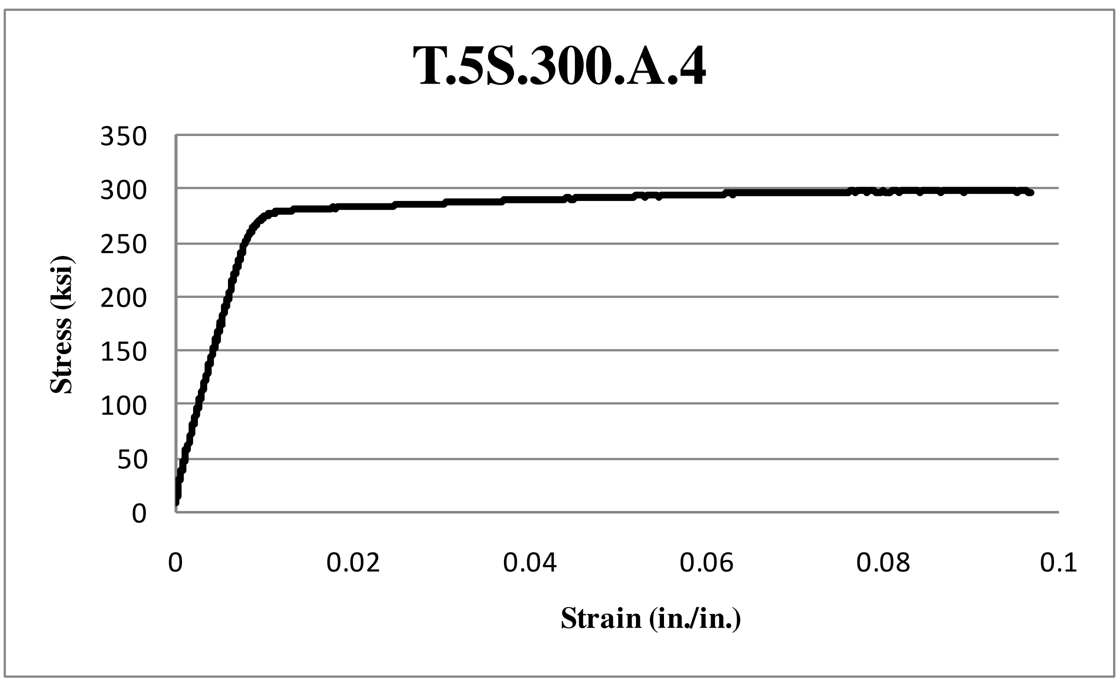

Figure A.41 Stress-Strain Curve for T.5S.300.A.4

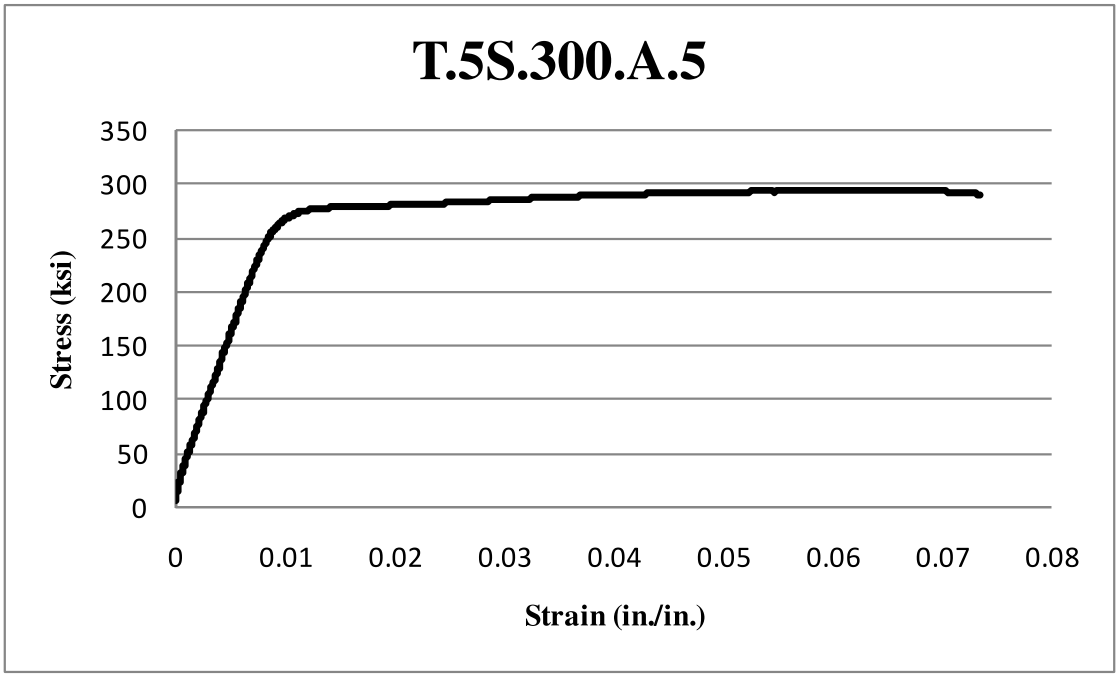

Figure A.42 Stress-Strain Curve for T.5S.300.A.5

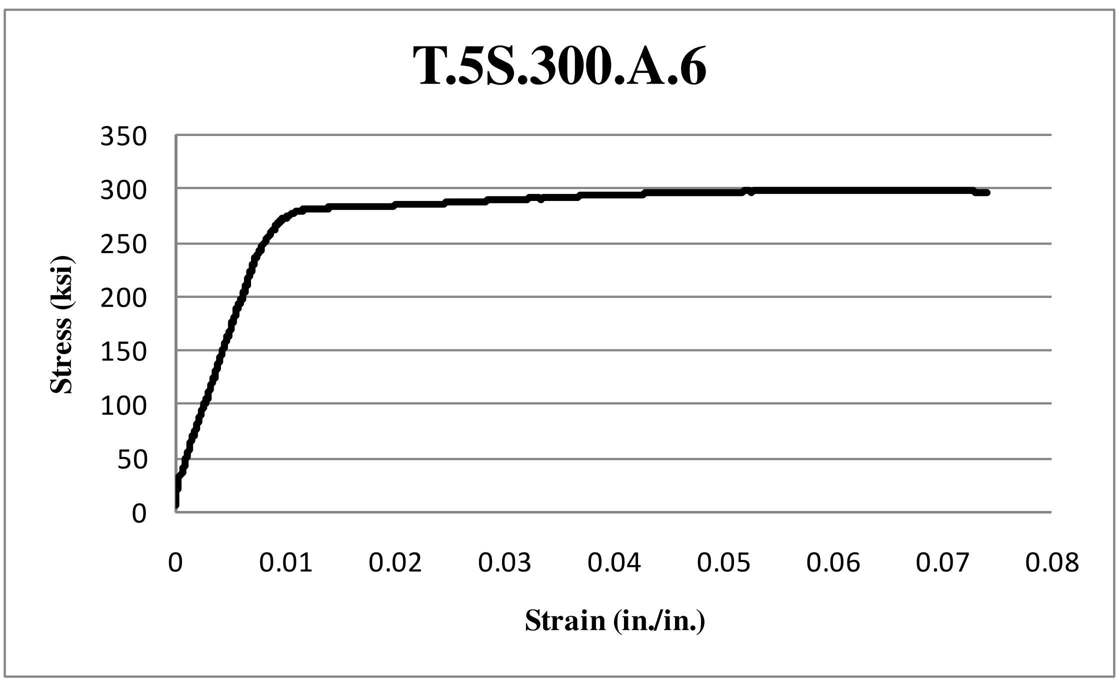

Figure A.43 Stress-Strain Curve for T.5S.300.A.6

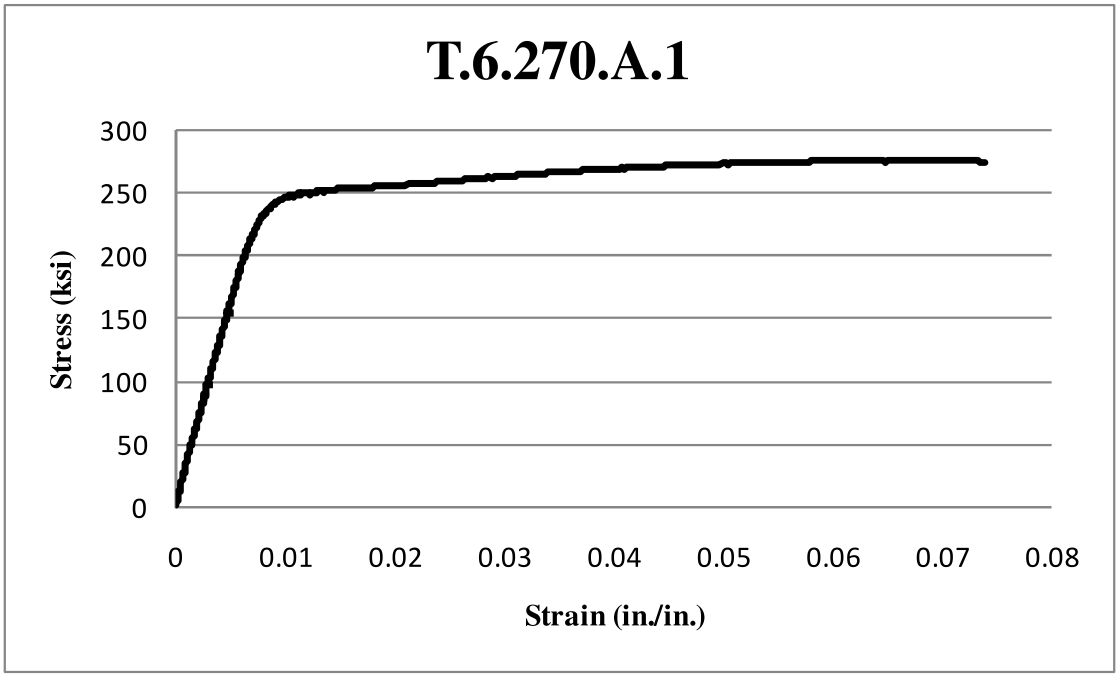

Figure A.44 Stress-Strain Curve for T.6.270.A.1

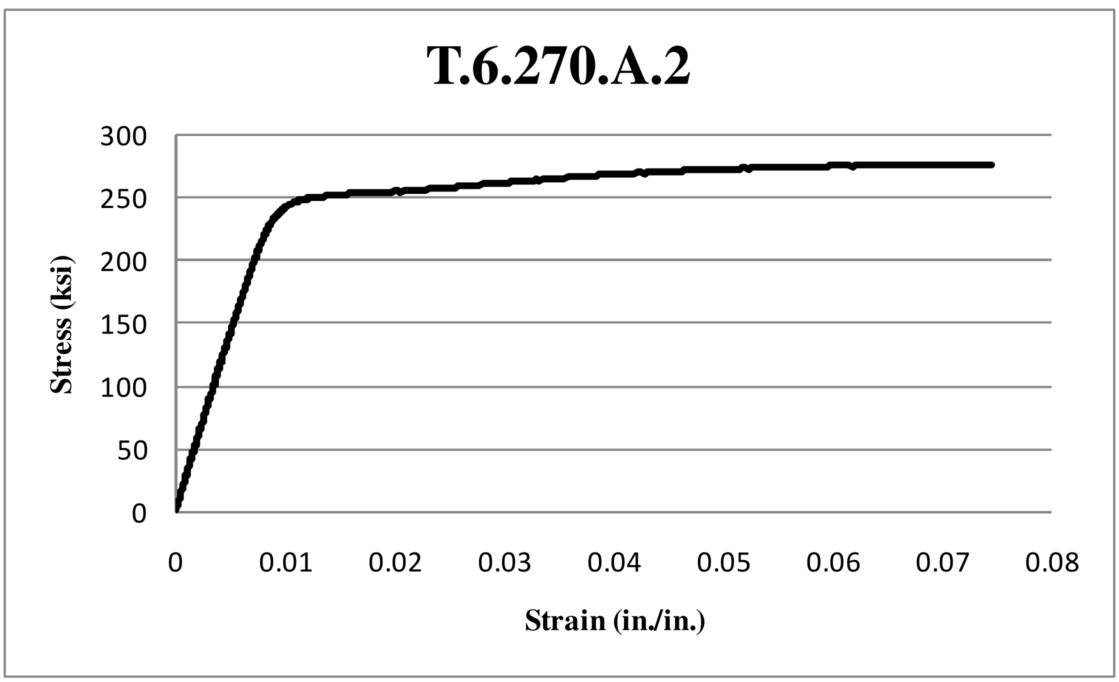

Figure A.45 Stress-Strain Curve for T.6.270.A.2

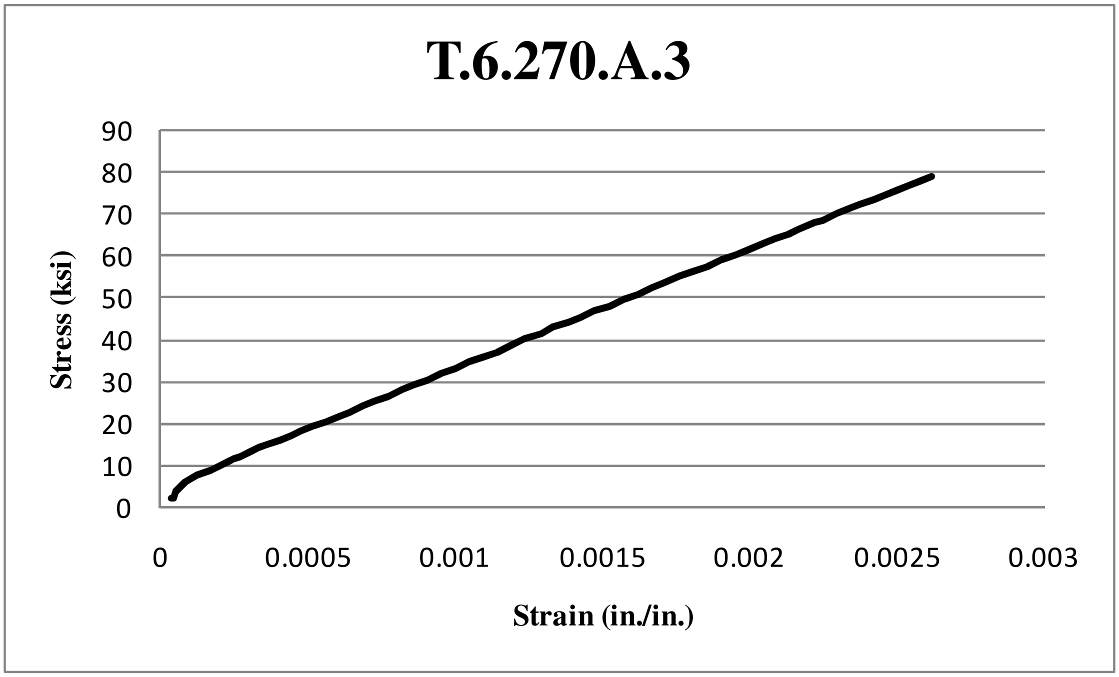

Figure A.46 Stress-Strain Curve for T.6.270.A.3

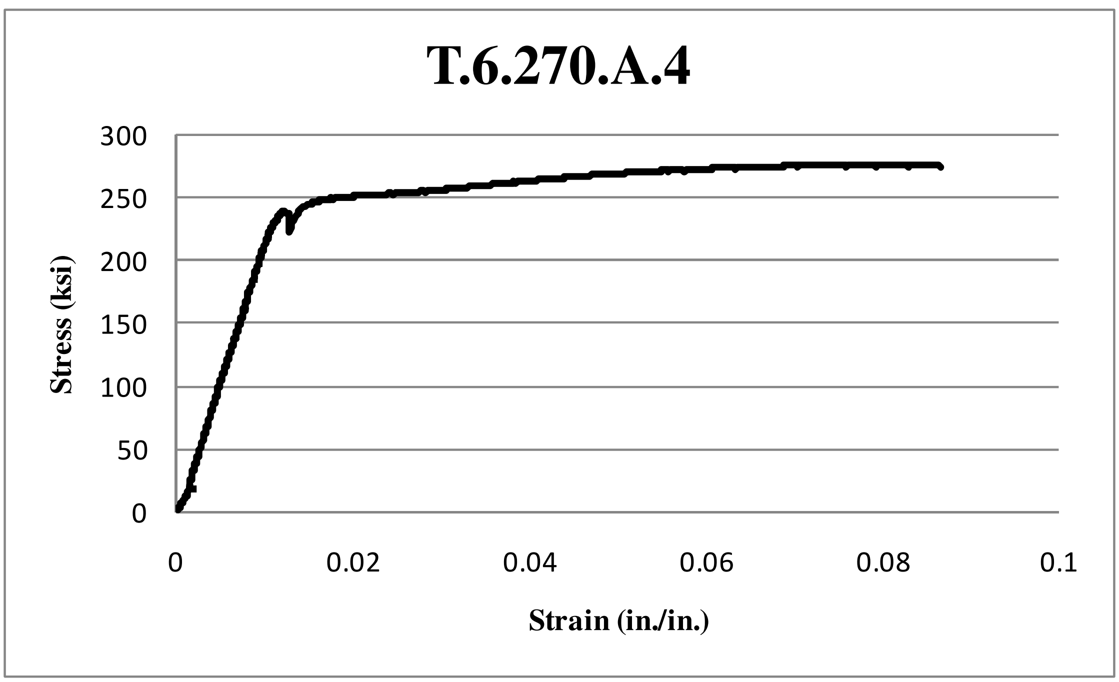

Figure A.47 Stress-Strain Curve for T.6.270.A.4

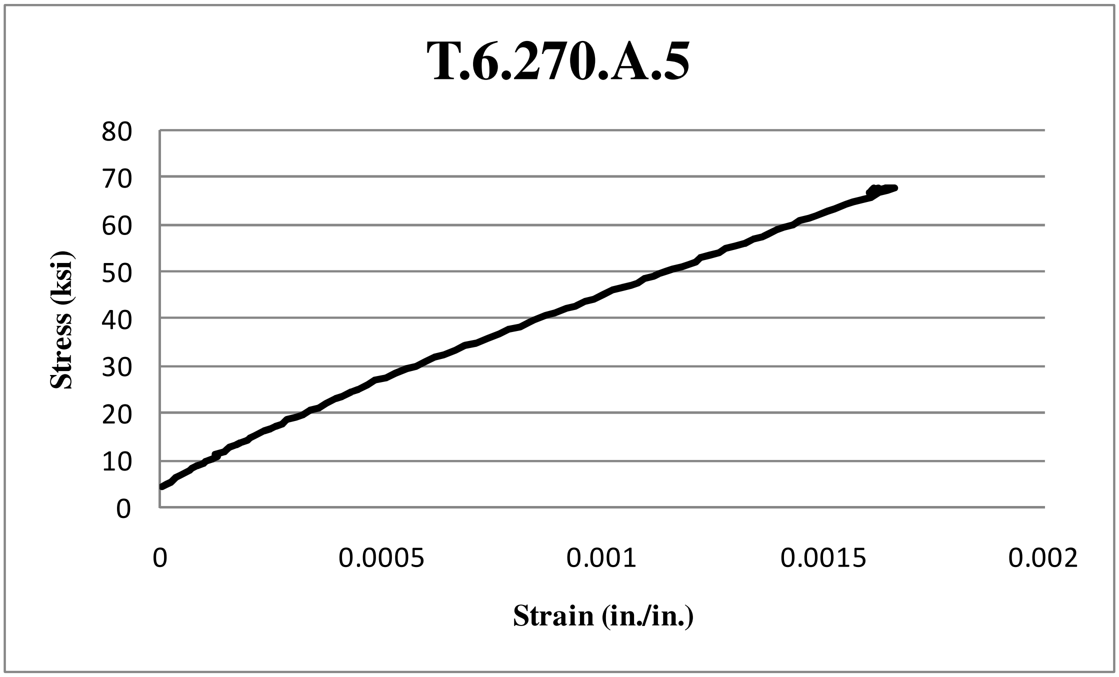

Figure A.48 Stress-Strain Curve for T.6.270.A.5

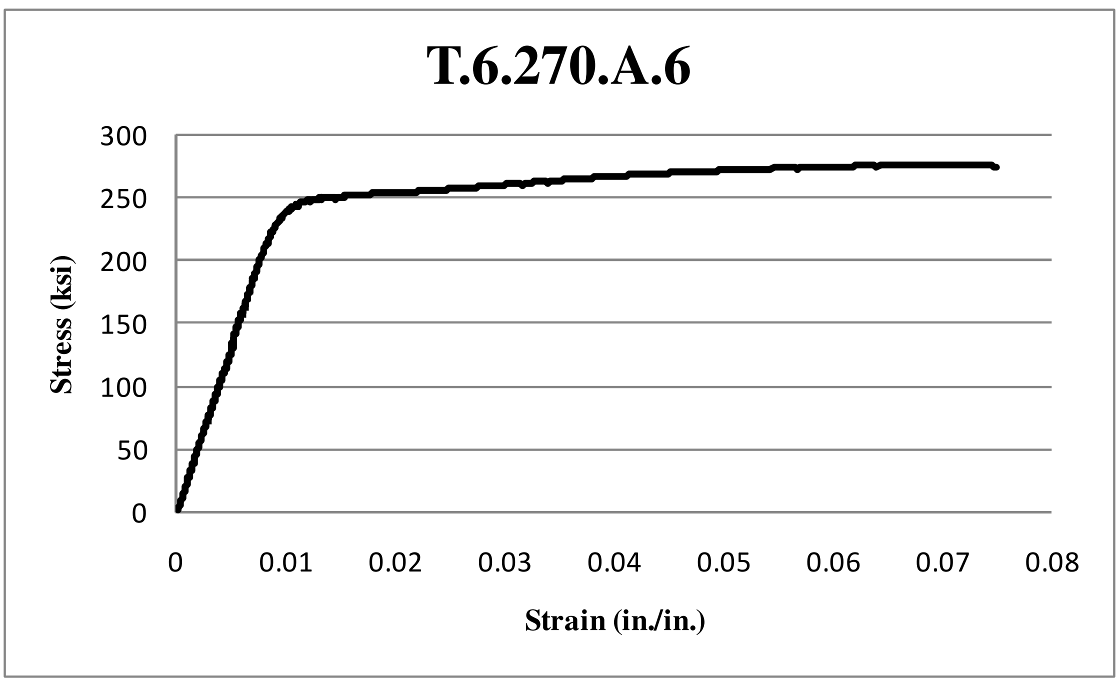

Figure A.49 Stress-Strain Curve for T.6.270.A.6

B. APPENDIX B: LOAD-DISPLACEMENT CURVES FOR NASP TESTS

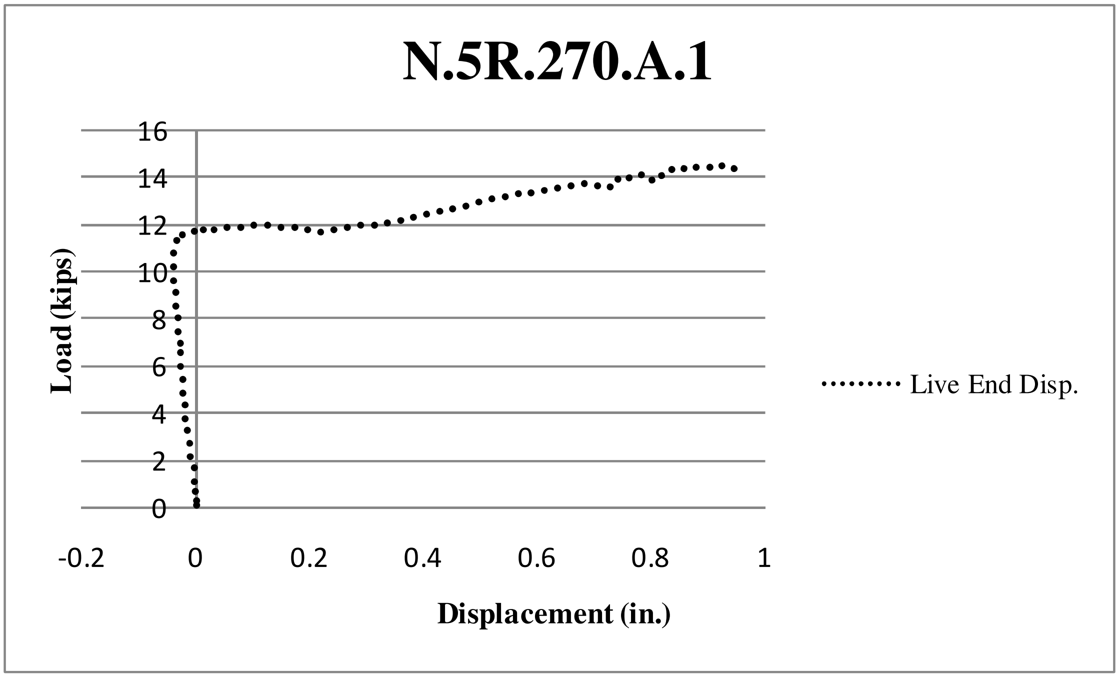

Figure B.1 Load vs. Displacement for N.5R.270.A.1

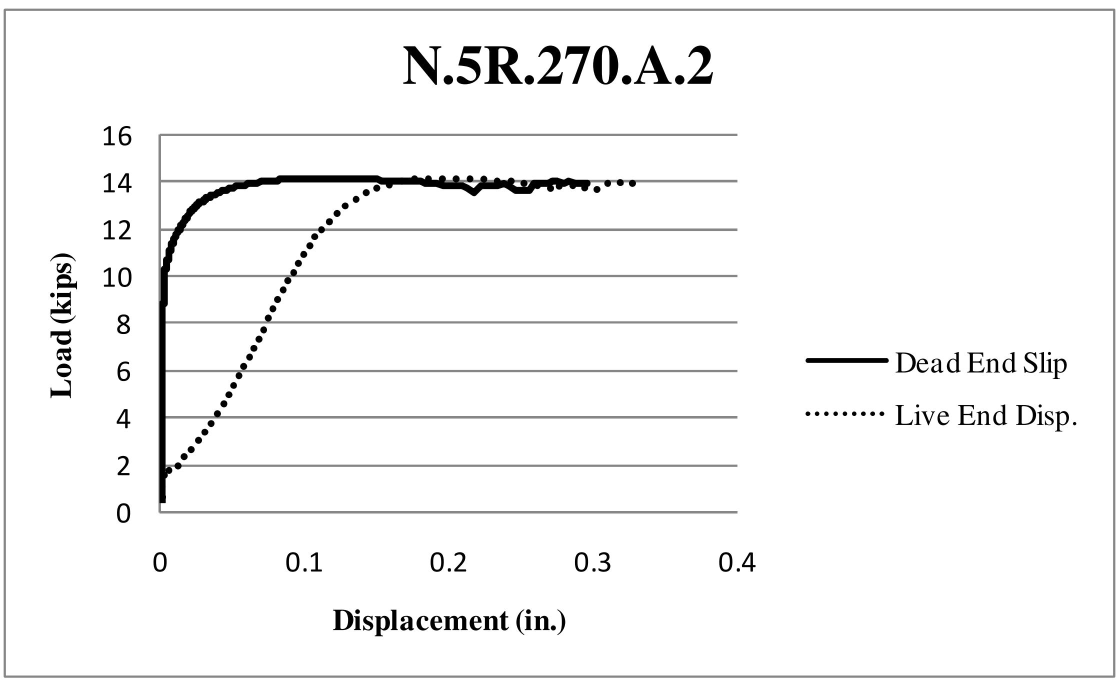

Figure B.2 Load vs. Displacement for N.5R.270.A.2

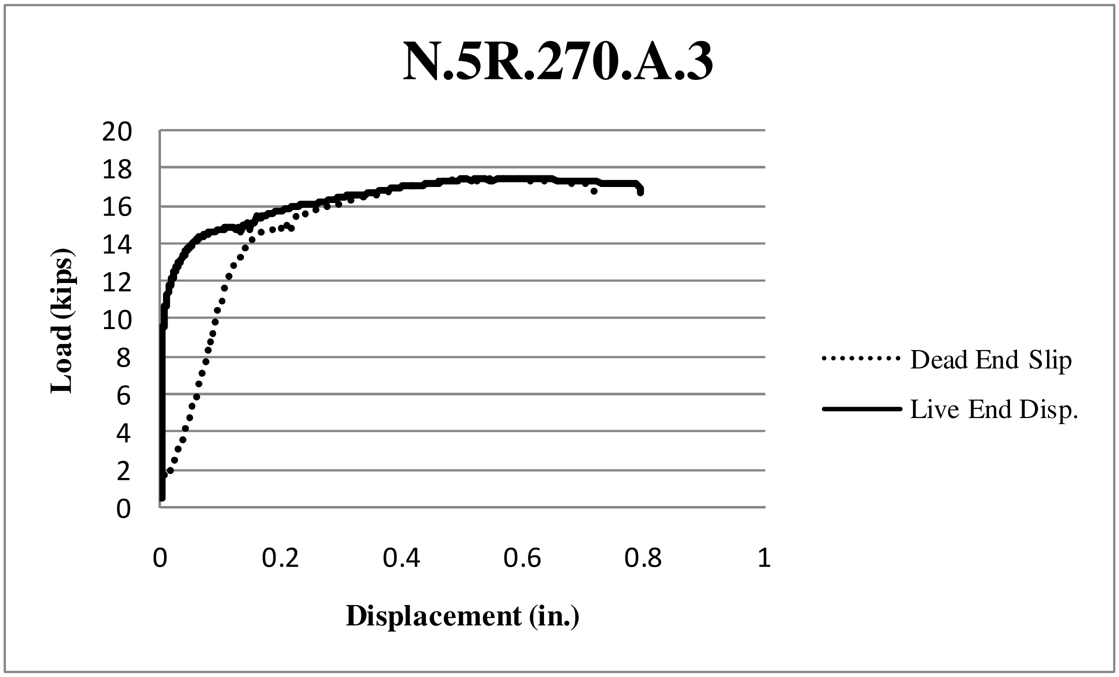

Figure B.3 Load vs. Displacement for N.5R.270.A.3

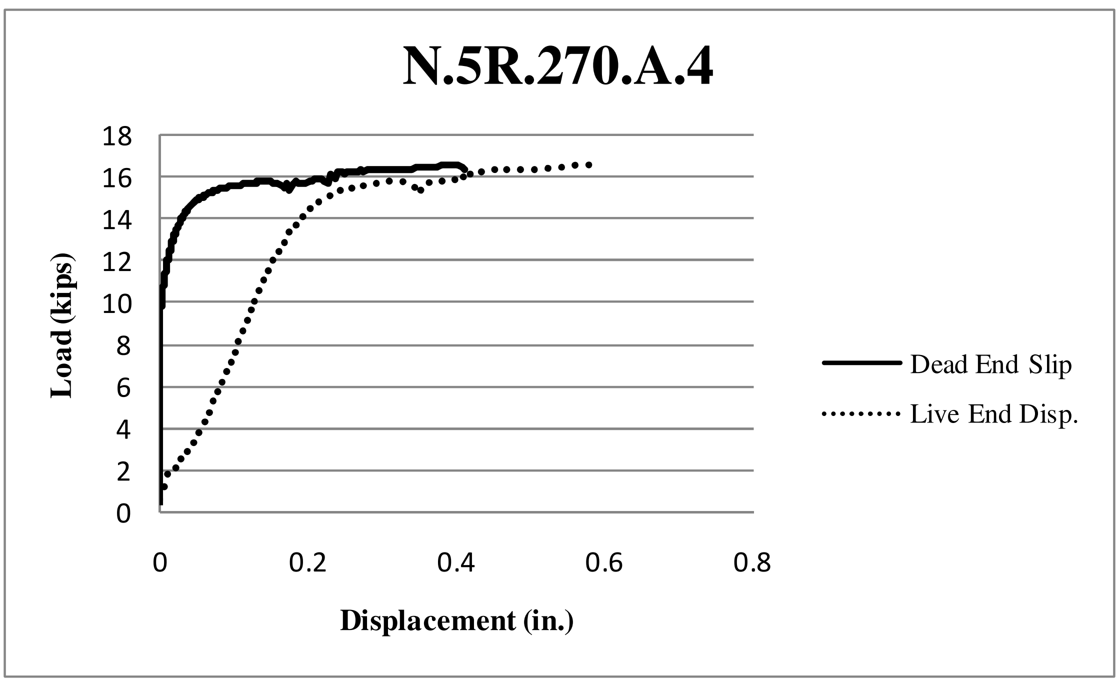

Figure B.4 Load vs. Displacement for N.5R.270.A.4

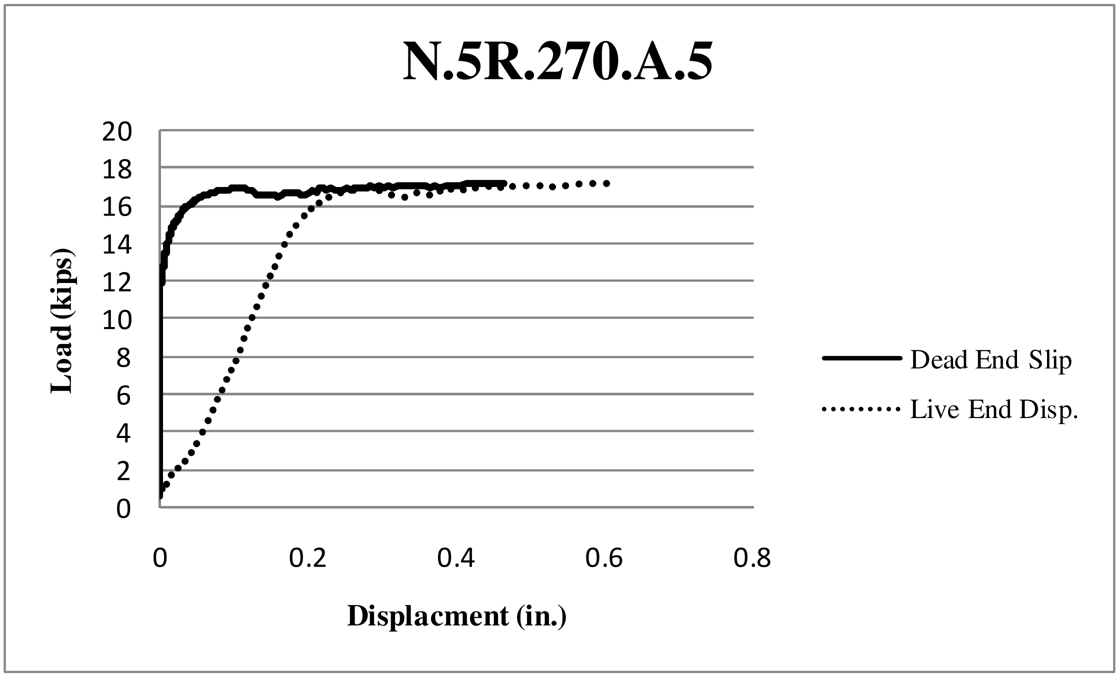

Figure B.5 Load vs. Displacement for N.5R.270.A.5

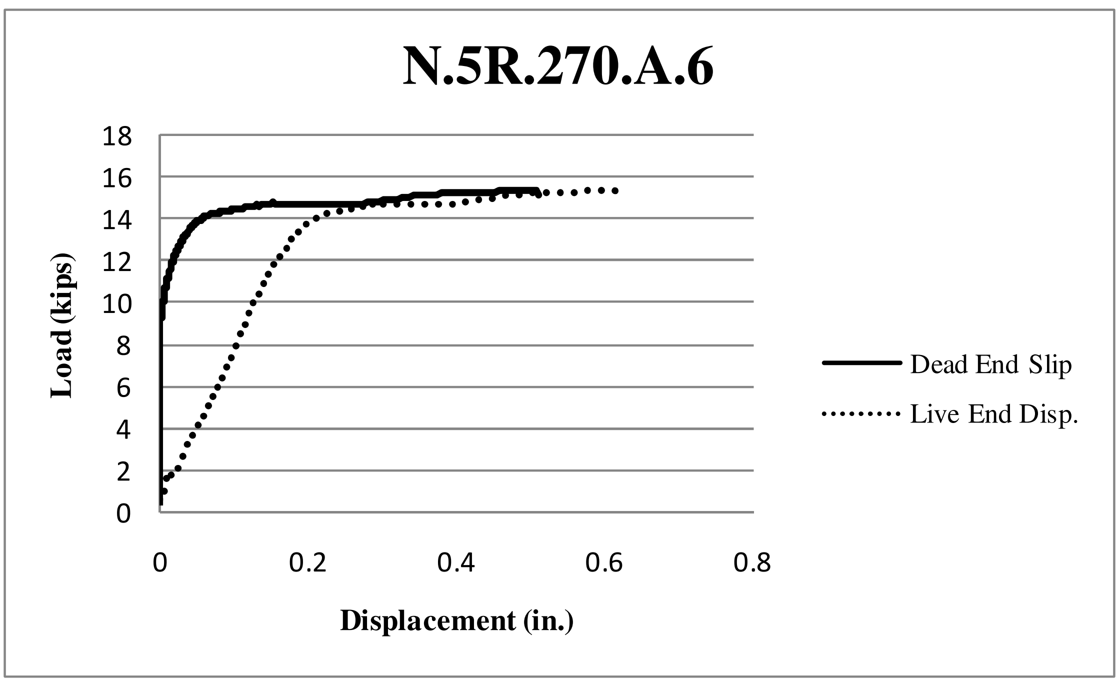

Figure B.6 Load vs. Displacement for N.5R.270.A.6

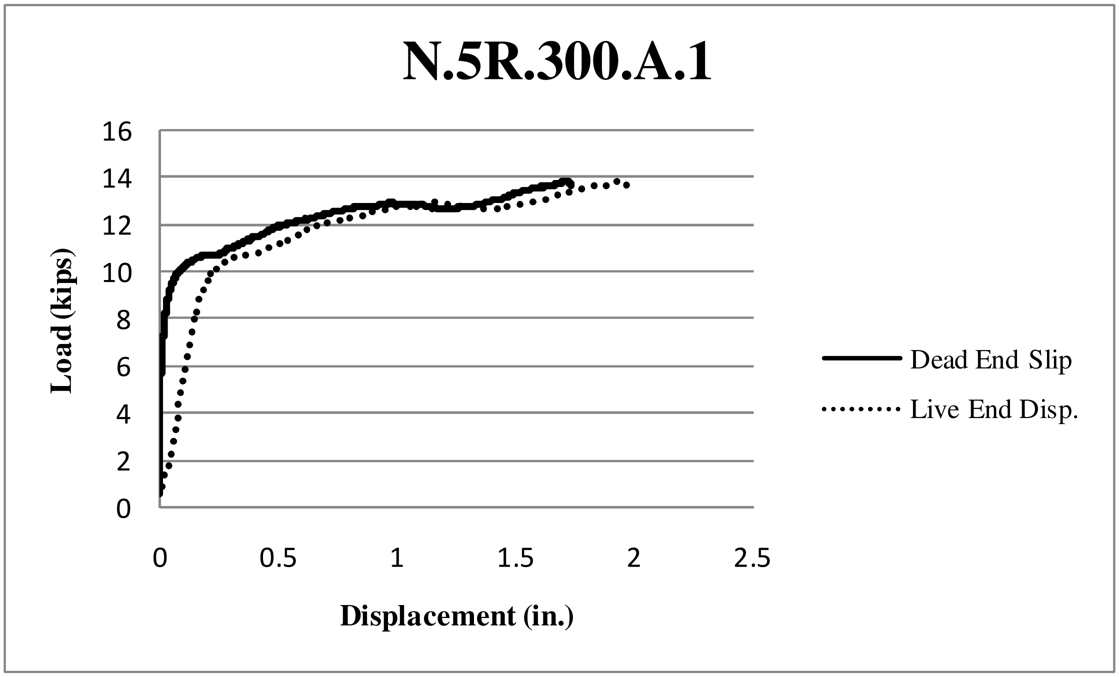

Figure B.7 Load vs. Displacement for N.5R.300.A.1

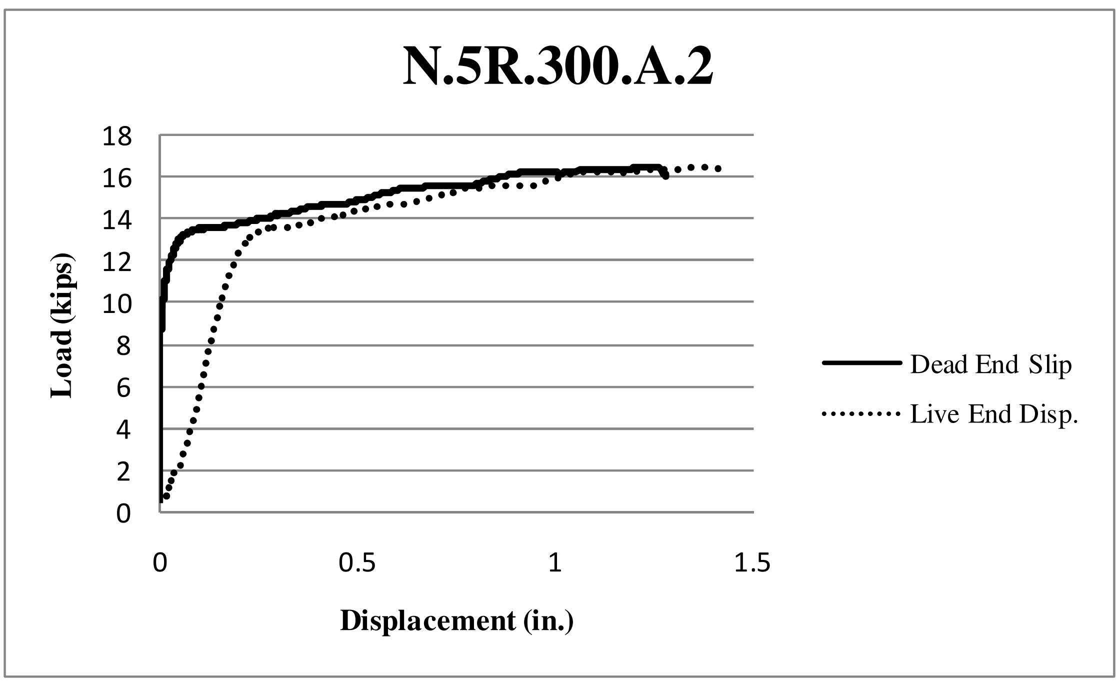

Figure B.8 Load vs. Displacement for N.5R.300.A.2

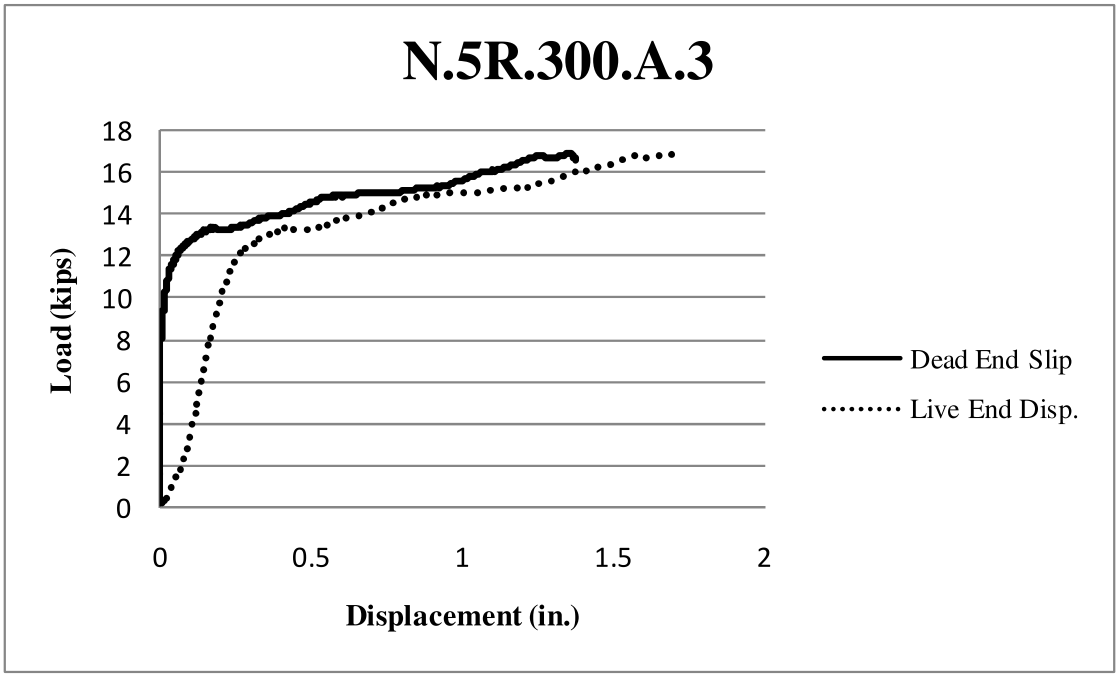

Figure B.9 Load vs. Displacement for N.5R.300.A.3

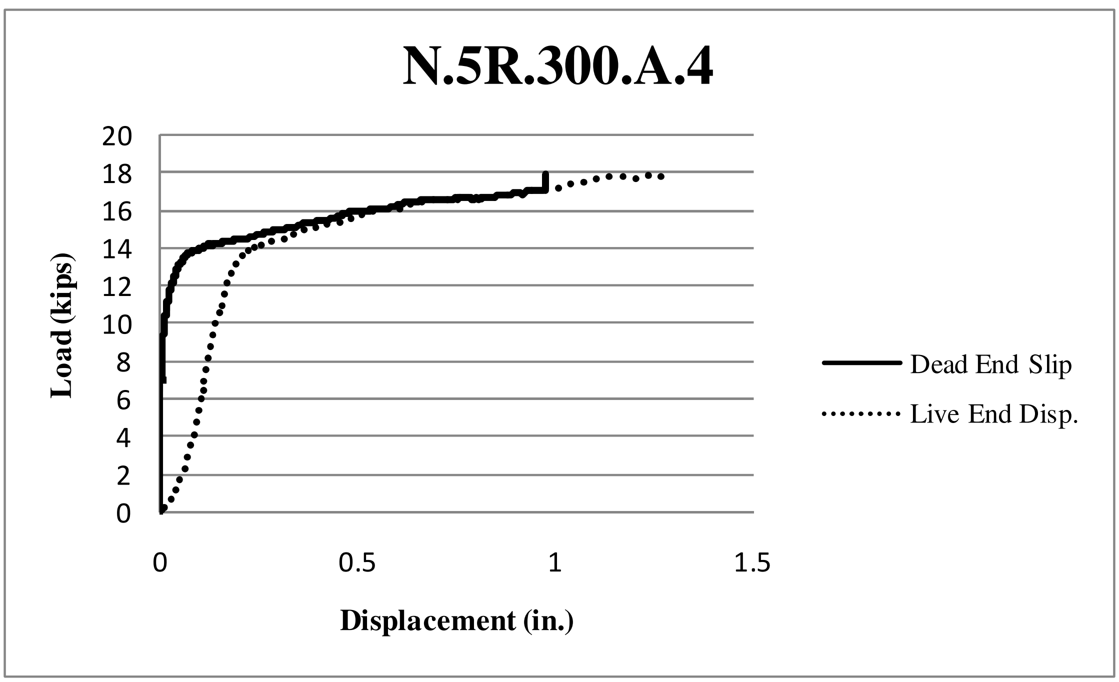

Figure B.10 Load vs. Displacement for N.5R.300.A.4

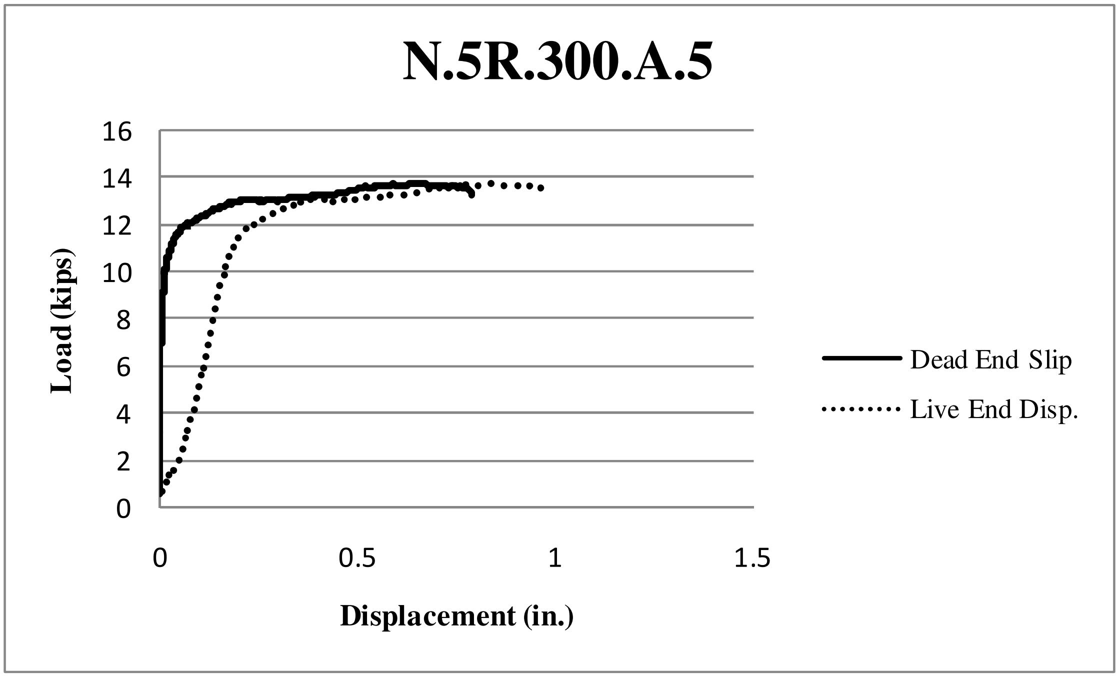

Figure B.11 Load vs. Displacement for N.5R.300.A.5

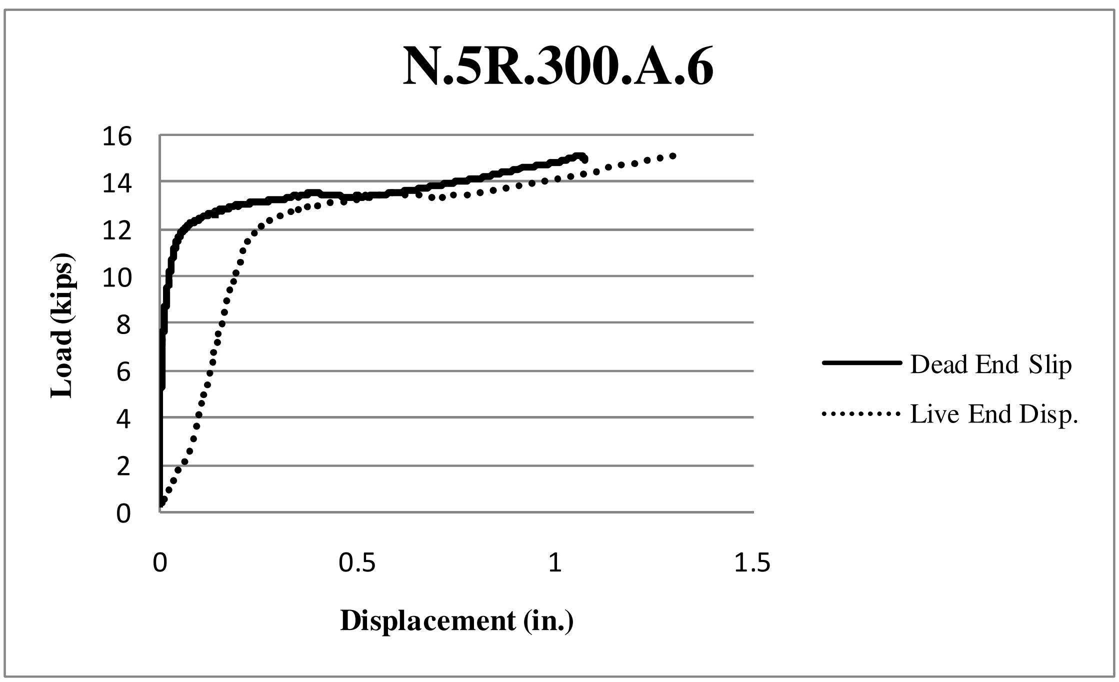

Figure B.12 Load vs. Displacement for N.5R.300.A.6

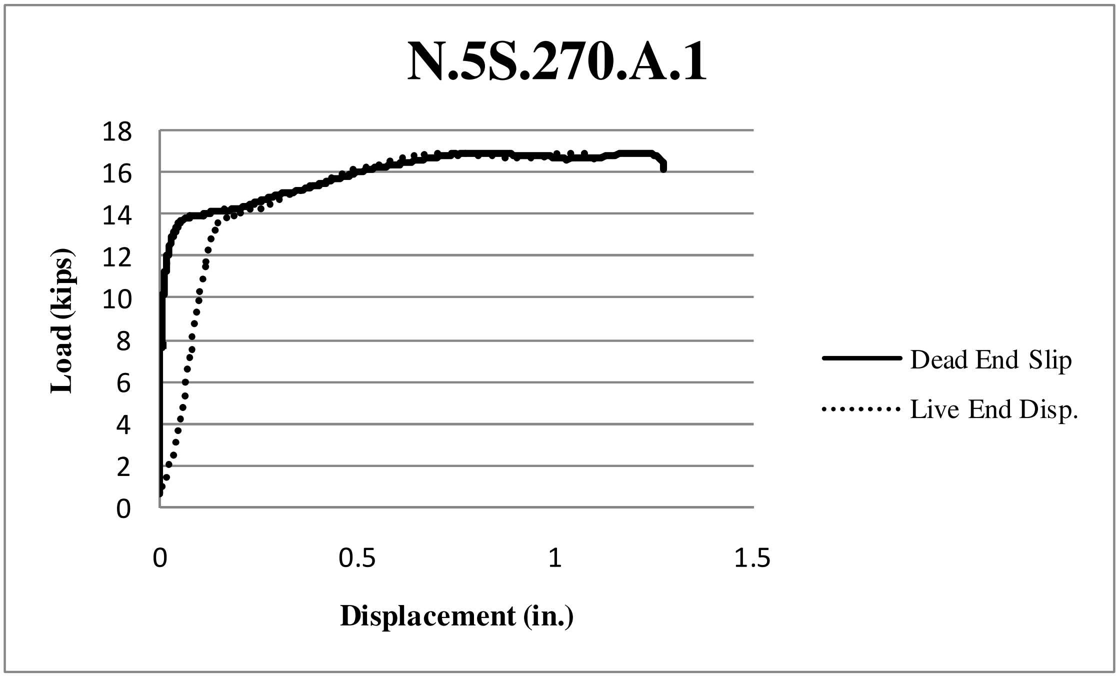

Figure B.13 Load vs. Displacement for N.5S.270.A.1

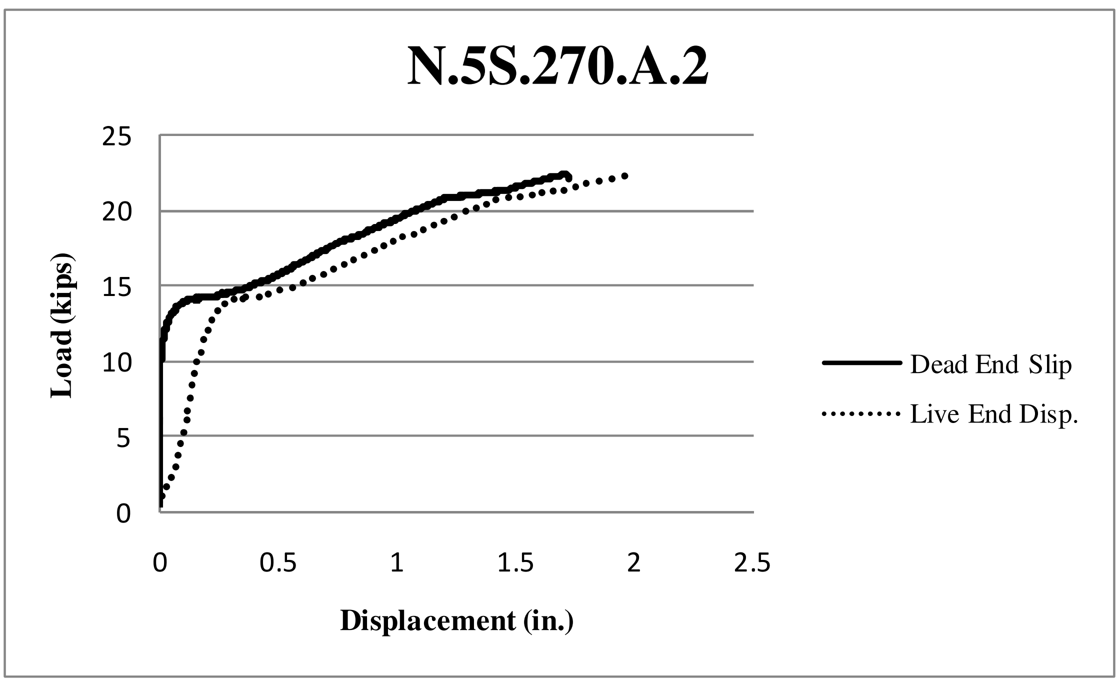

Figure B.14 Load vs. Displacement for N.5S.270.A.2

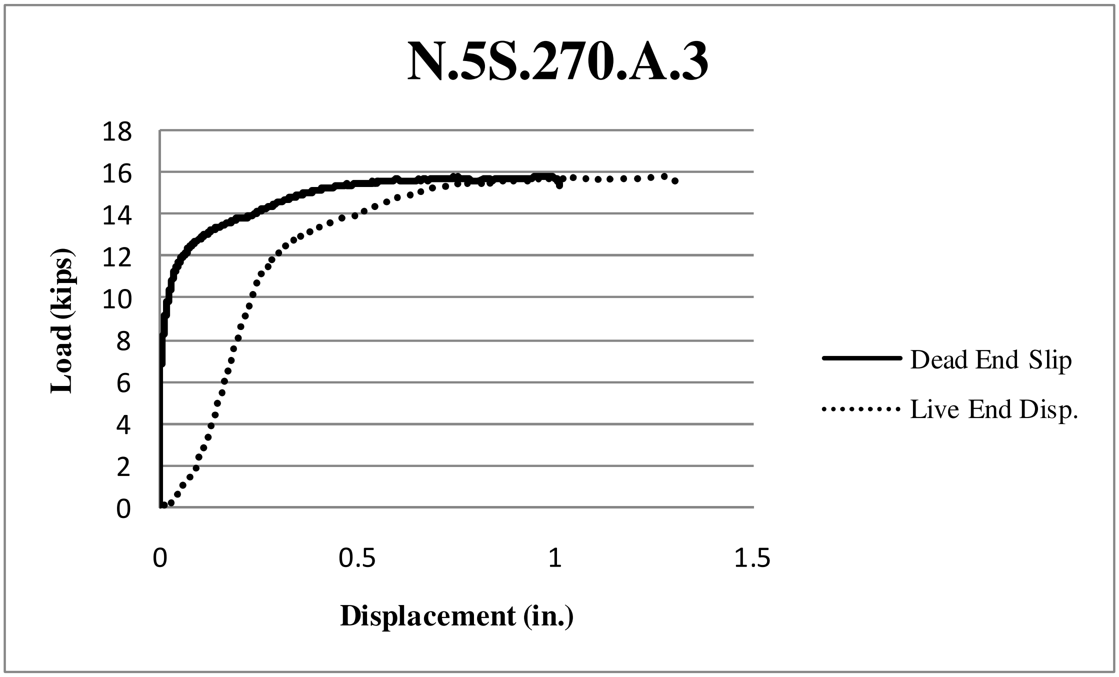

Figure B.15 Load vs. Displacement for N.5S.270.A.3

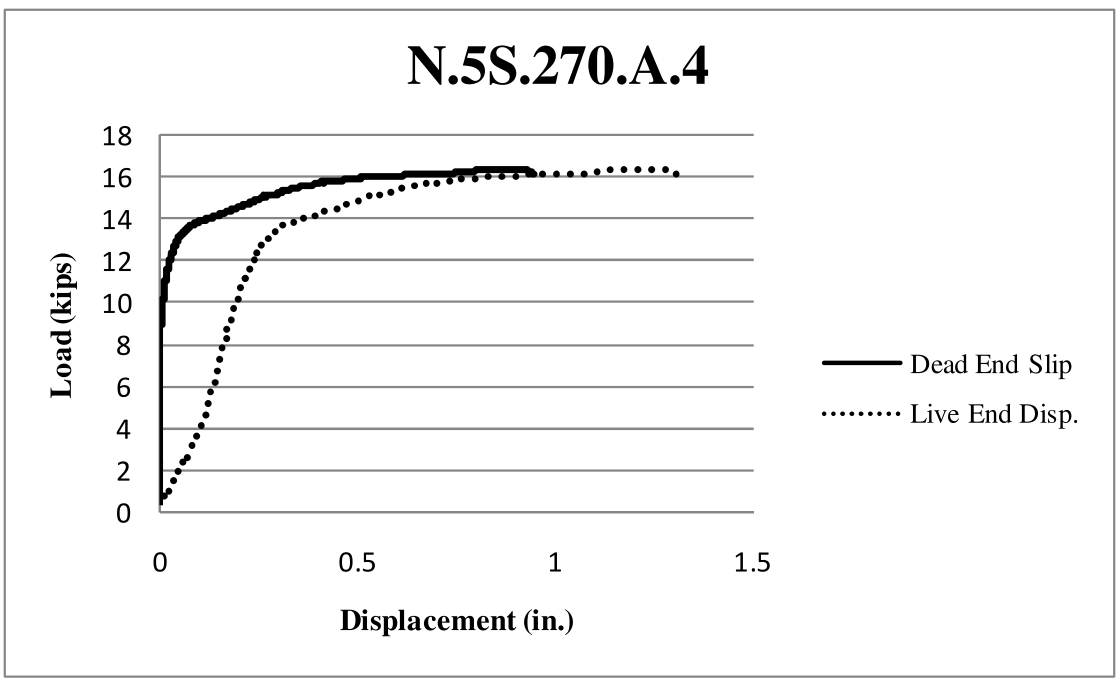

Figure B.16 Load vs. Displacement for N.5S.270.A.4

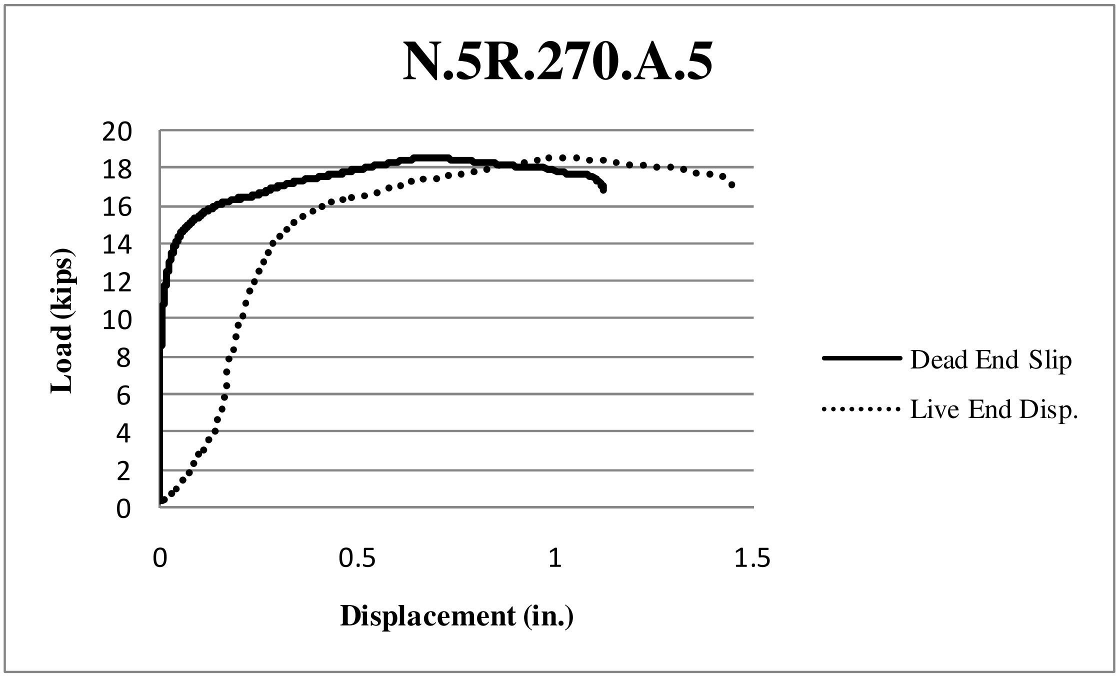

Figure B.17 Load vs. Displacement for N.5S.270.A.5

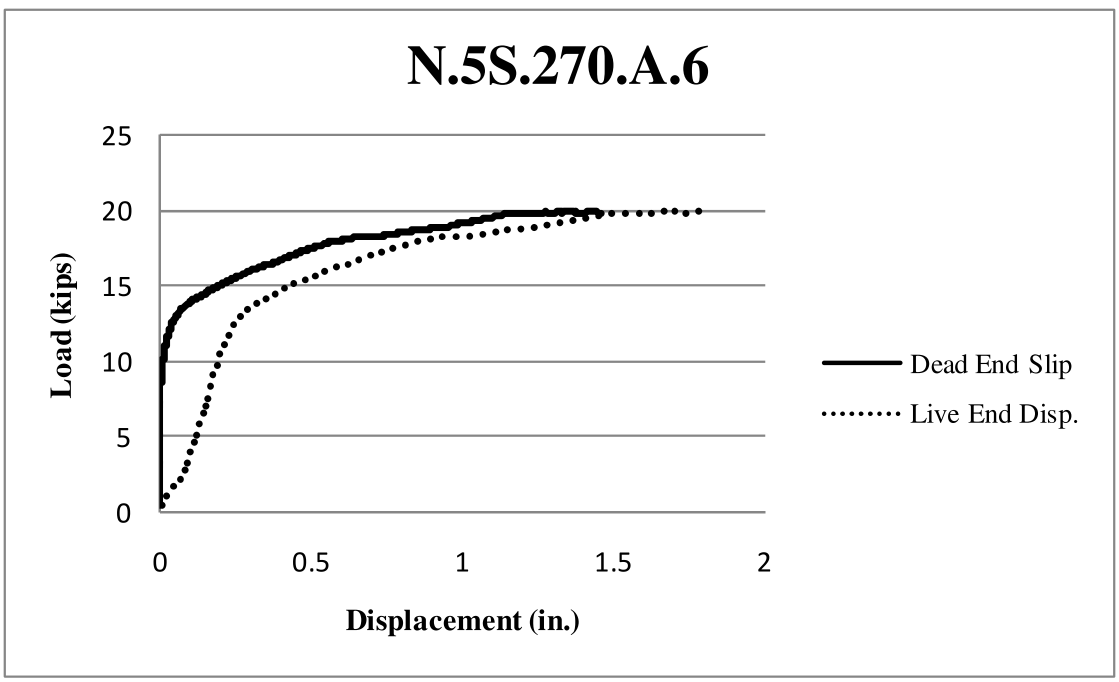

Figure B.18 Load vs. Displacement for N.5S.270.A.6

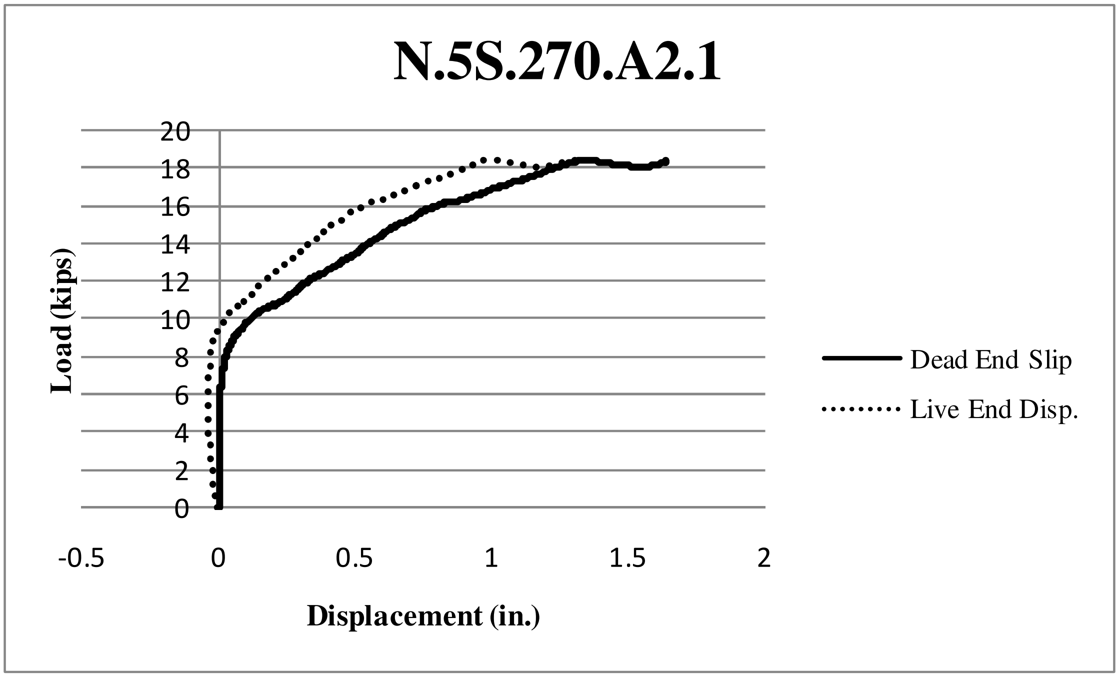

Figure B.19 Load vs. Displacment for N.5S.270.A2.1

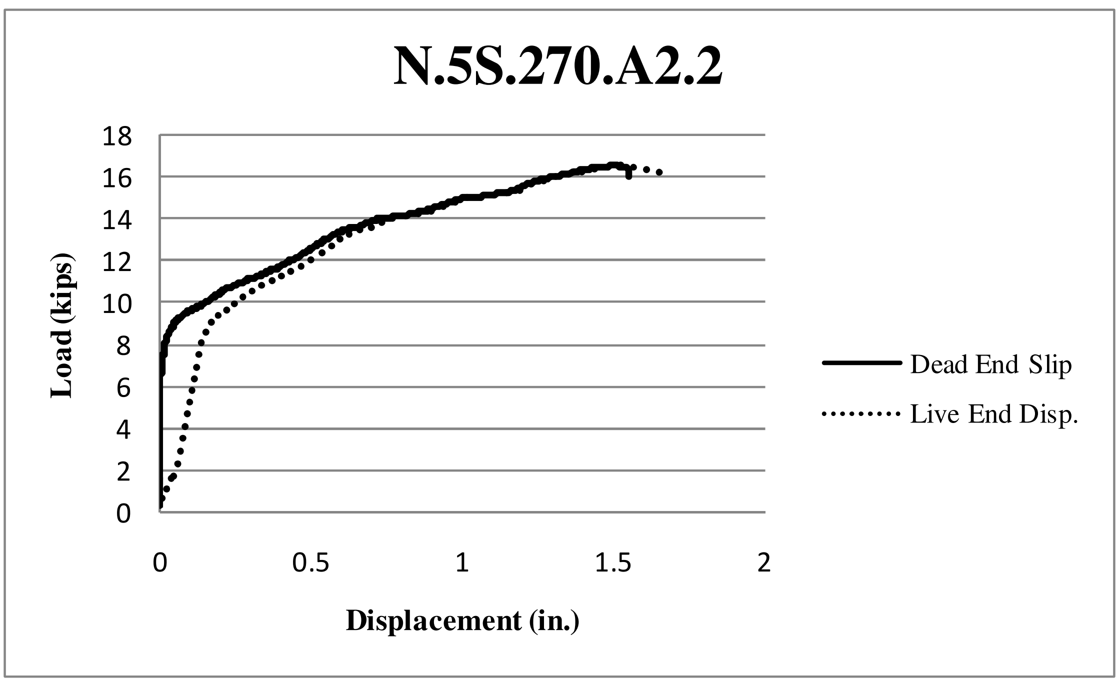

Figure B.20 Load vs. Displacement for N.5S.270.A2.2

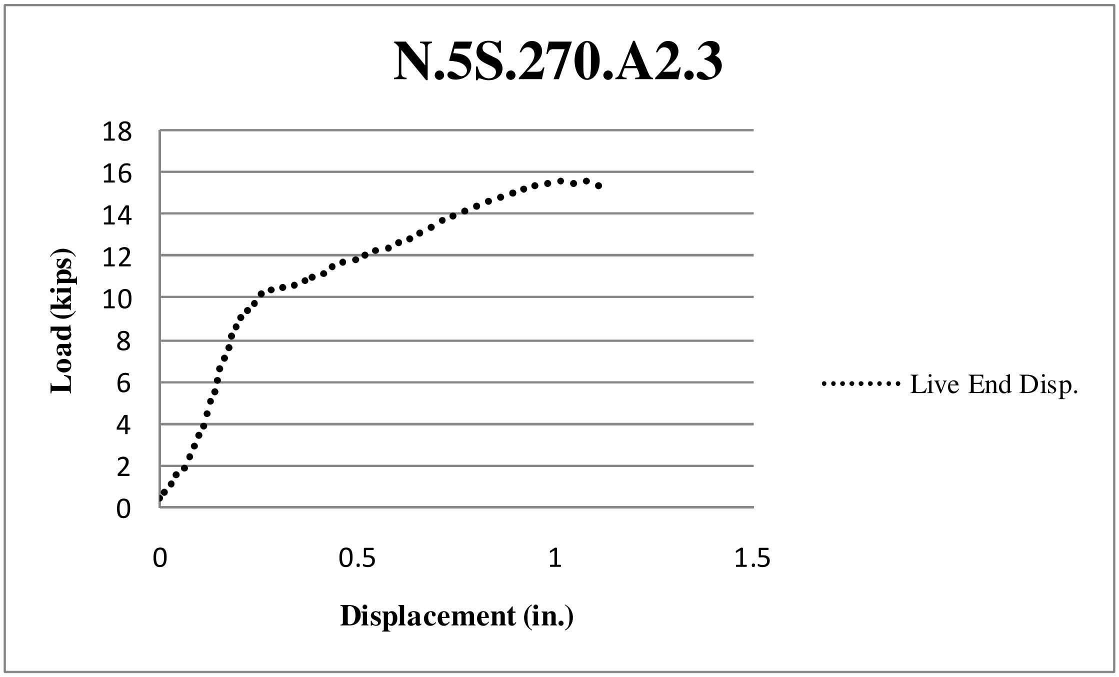

Figure B.21 Load vs. Displacment for N.5S.270.A2.3

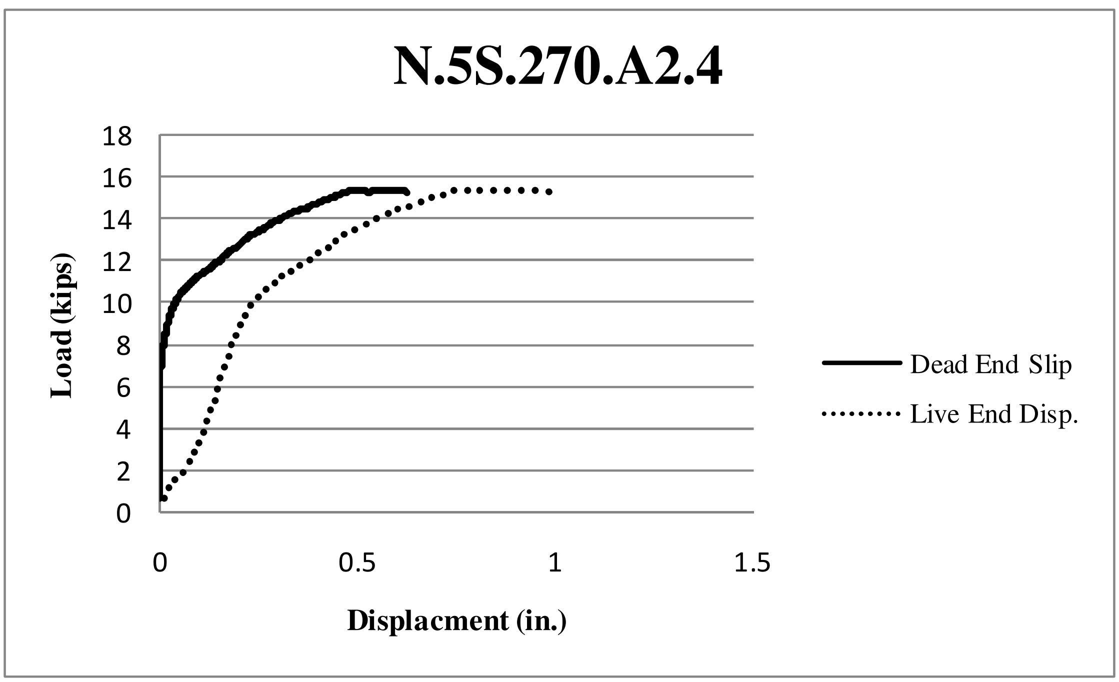

Figure B.22 Load vs. Displacement for N.5S.270.A2.4

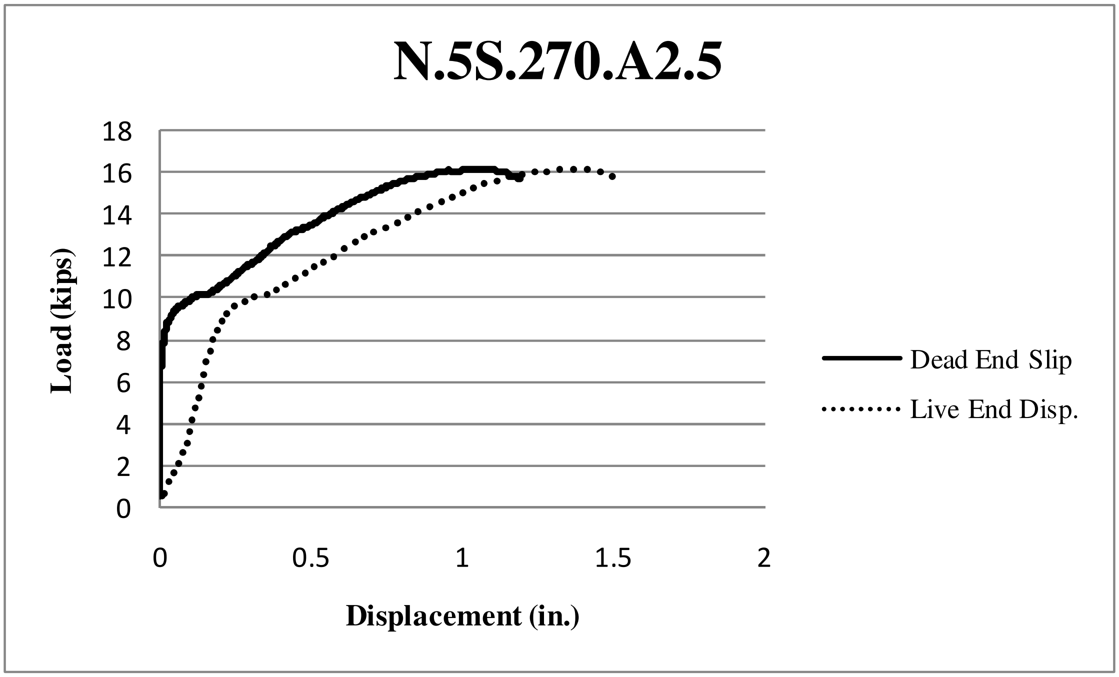

Figure B.23 Load vs. Displacement for N.5S.270.A2.5

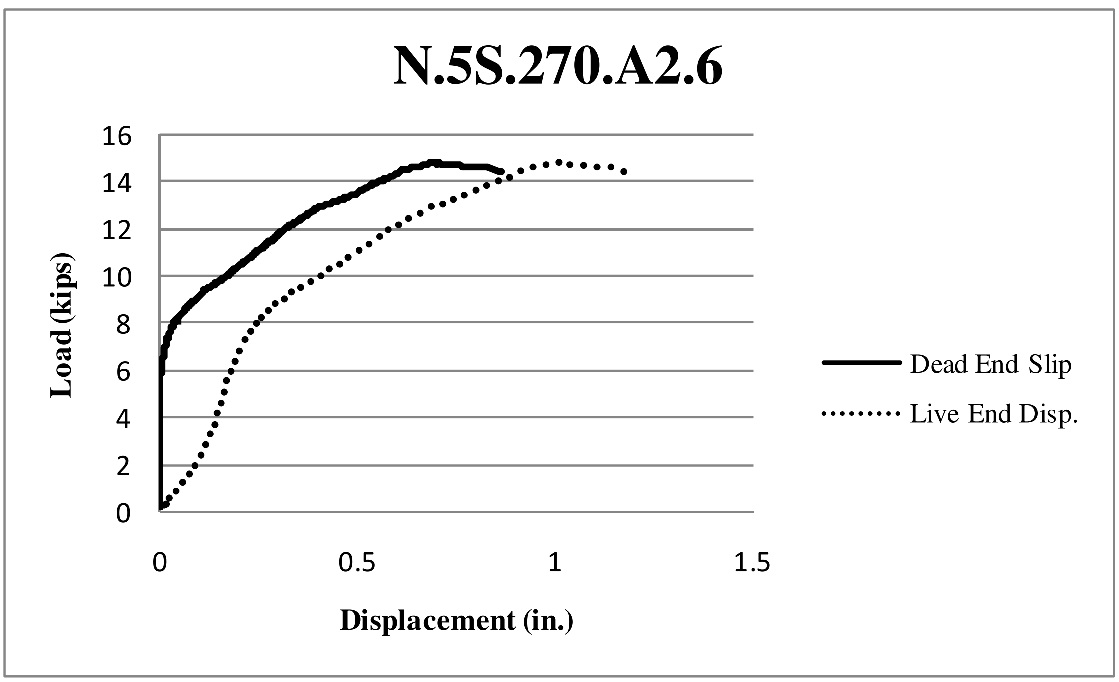

Figure B.24 Load vs. Displacement for N.5S.270.A2.6

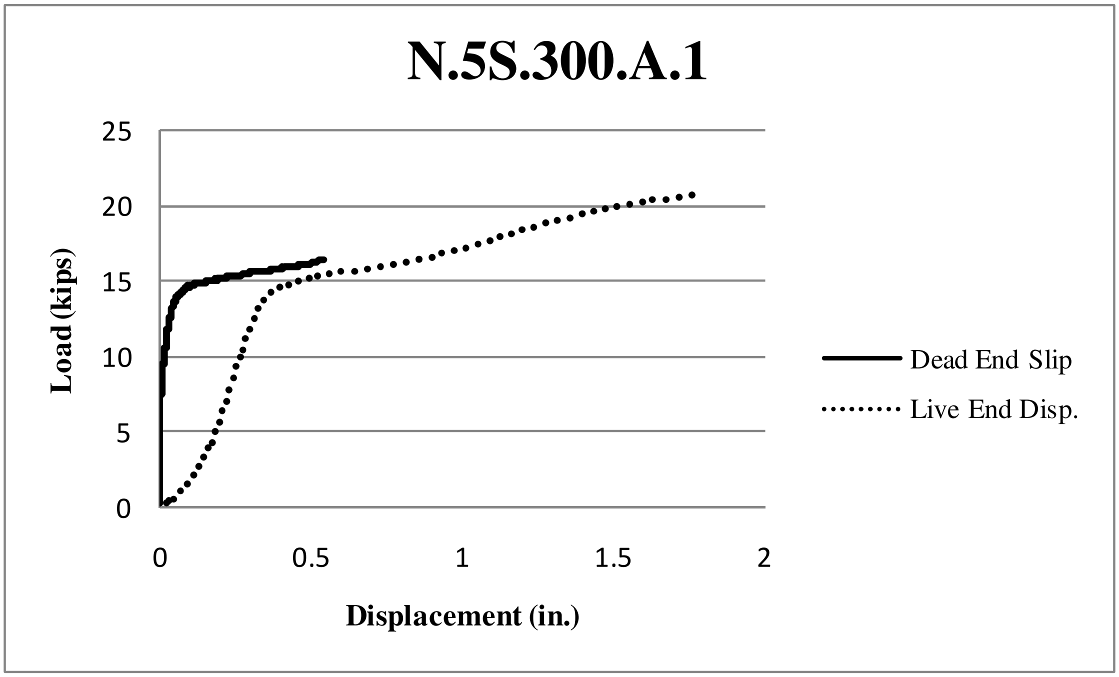

Figure B.25 Load vs. Displacement for N.5S.300.A.1

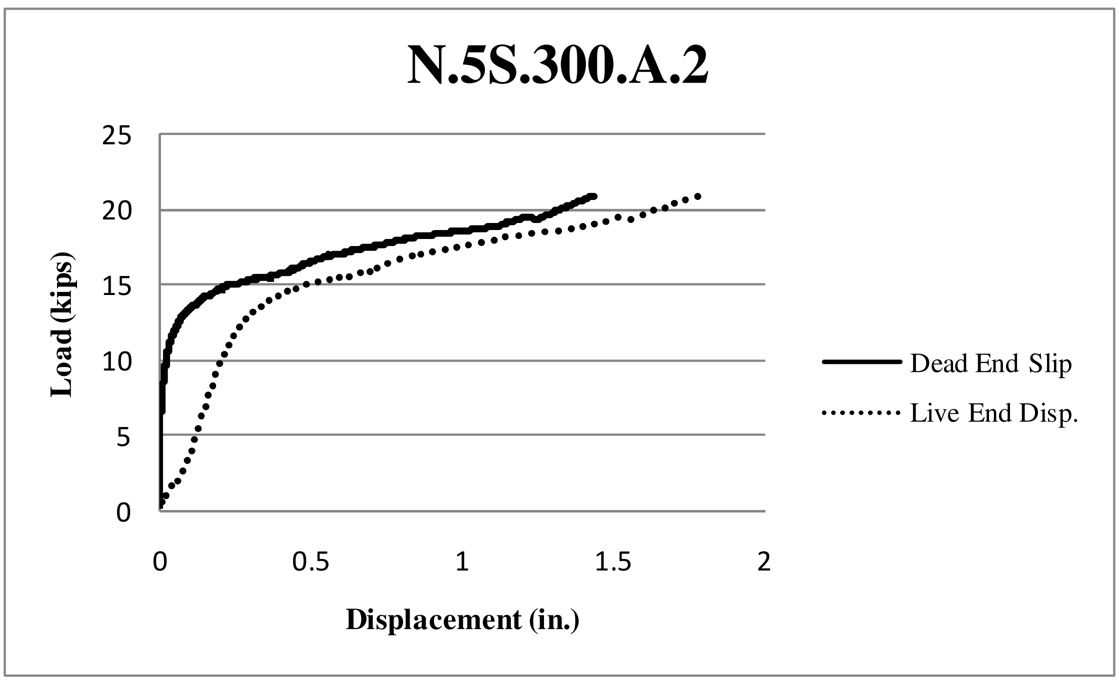

Figure B.26 Load vs. Displacement for N.5S.300.A.2

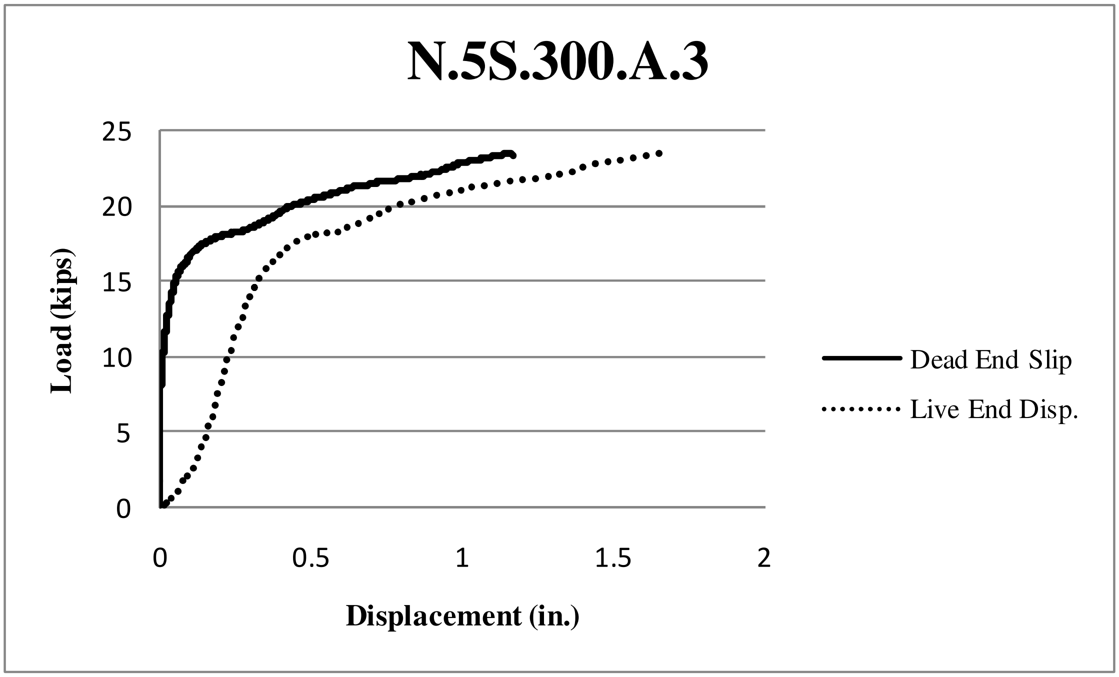

Figure B.27 Load vs. Displacement for N.5S.300.A.3

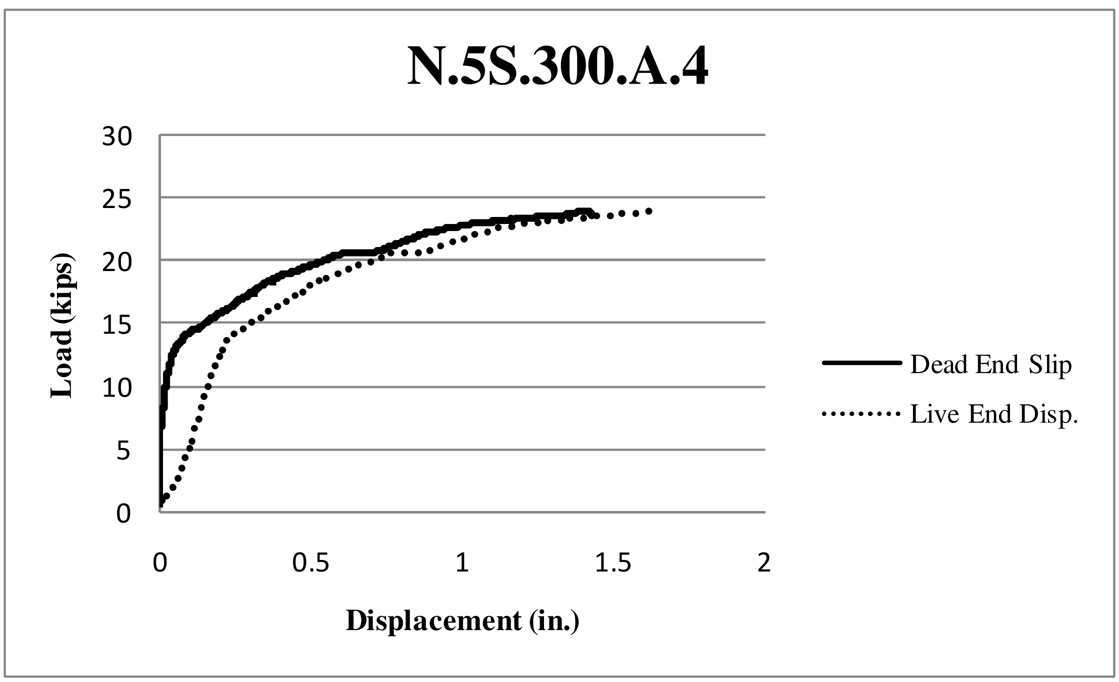

Figure B.28 Load vs. Displacement for N.5S.300.A.4

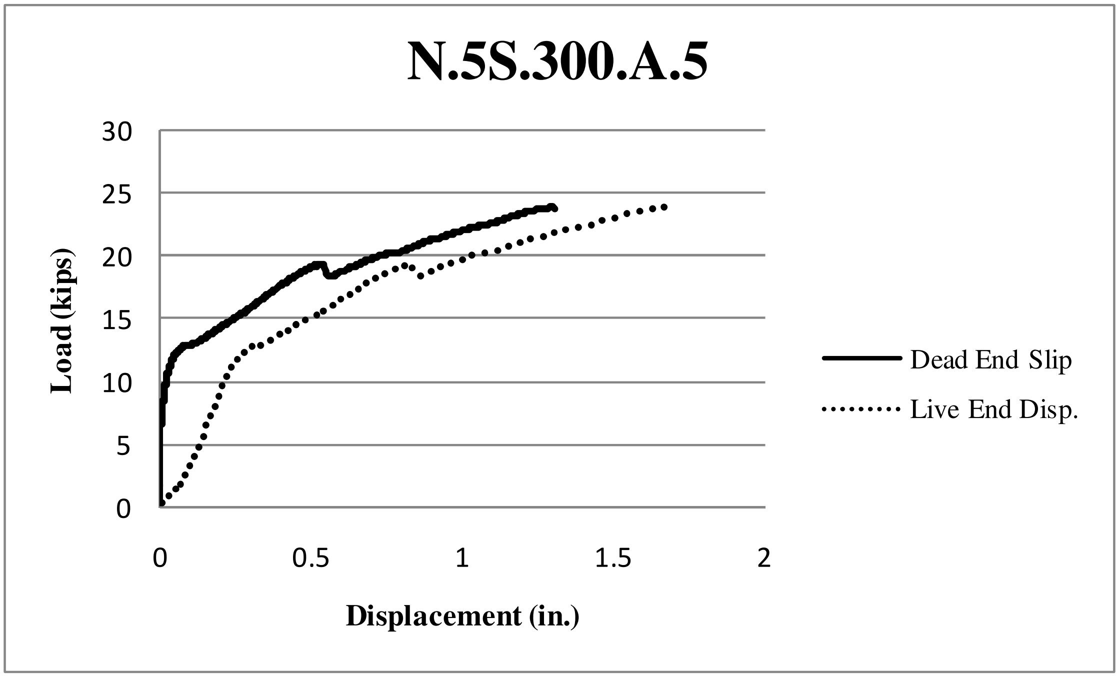

Figure B.29 Load vs. Displacement for N.5S.300.A.5

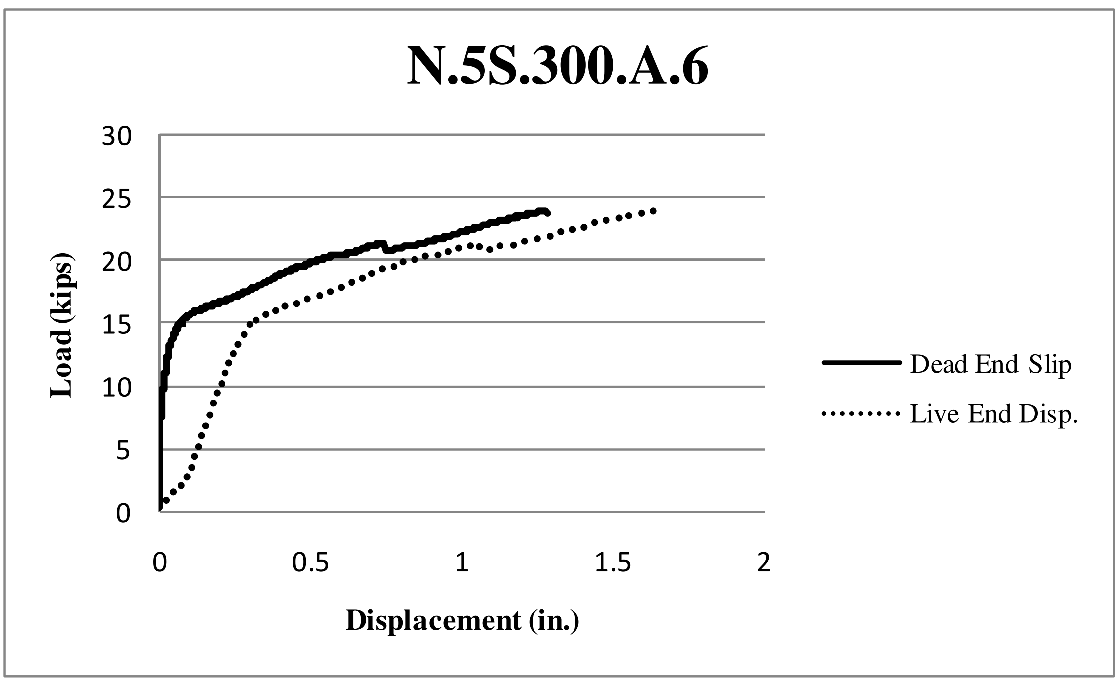

Figure B.30 Load vs. Displacement for N.5S.300.A.6

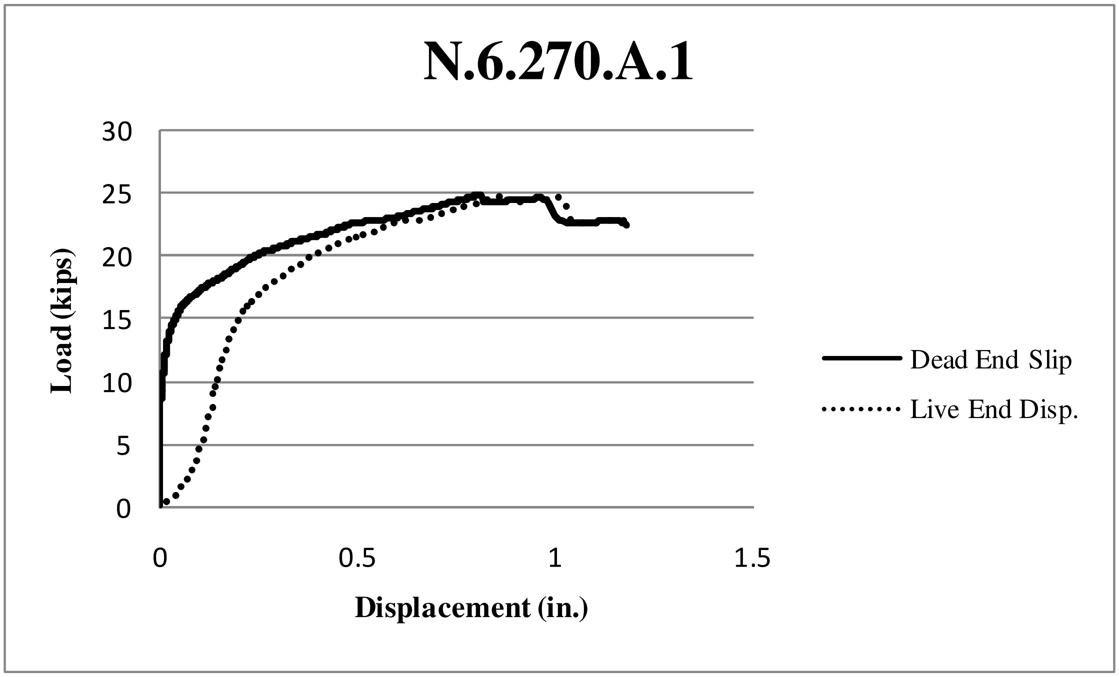

Figure B.31 Load vs. Displacement for N.6.270.A.1

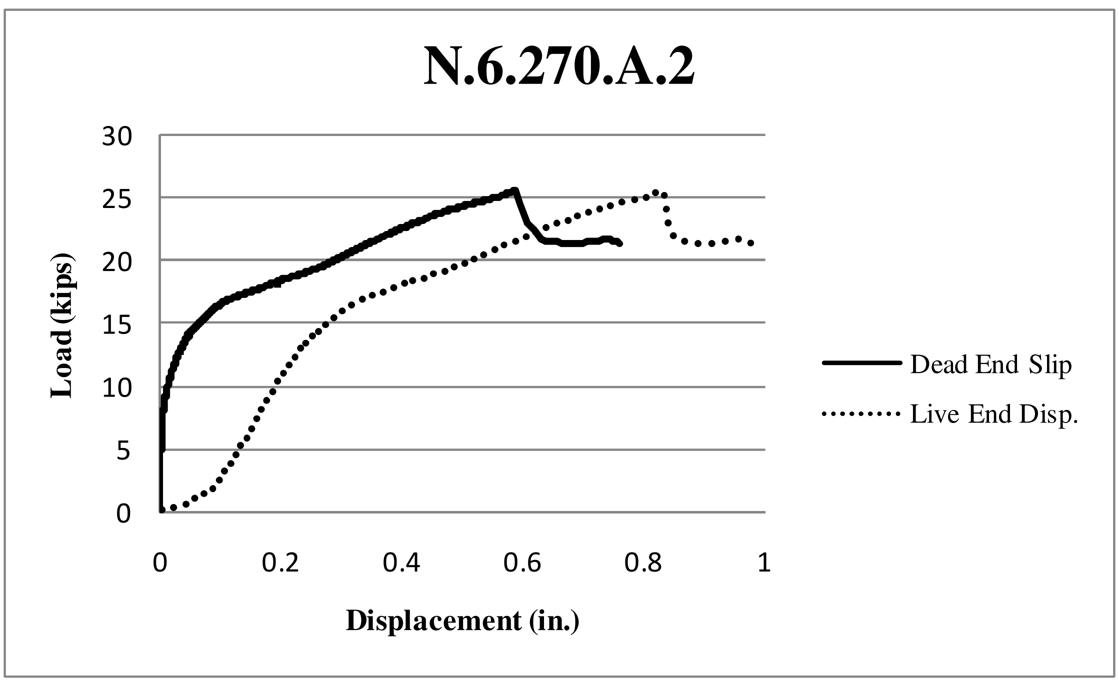

Figure B.32 Load vs. Displacement for N.6.270.A.2

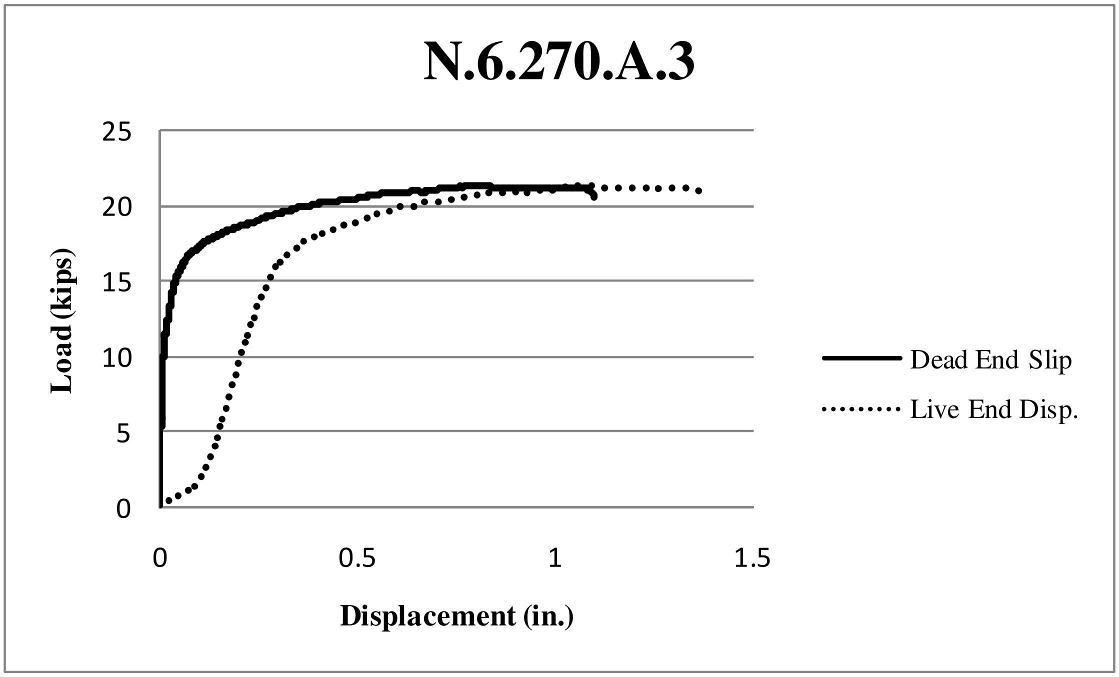

Figure B.33 Load vs. Displacement for N.6.270.A.3

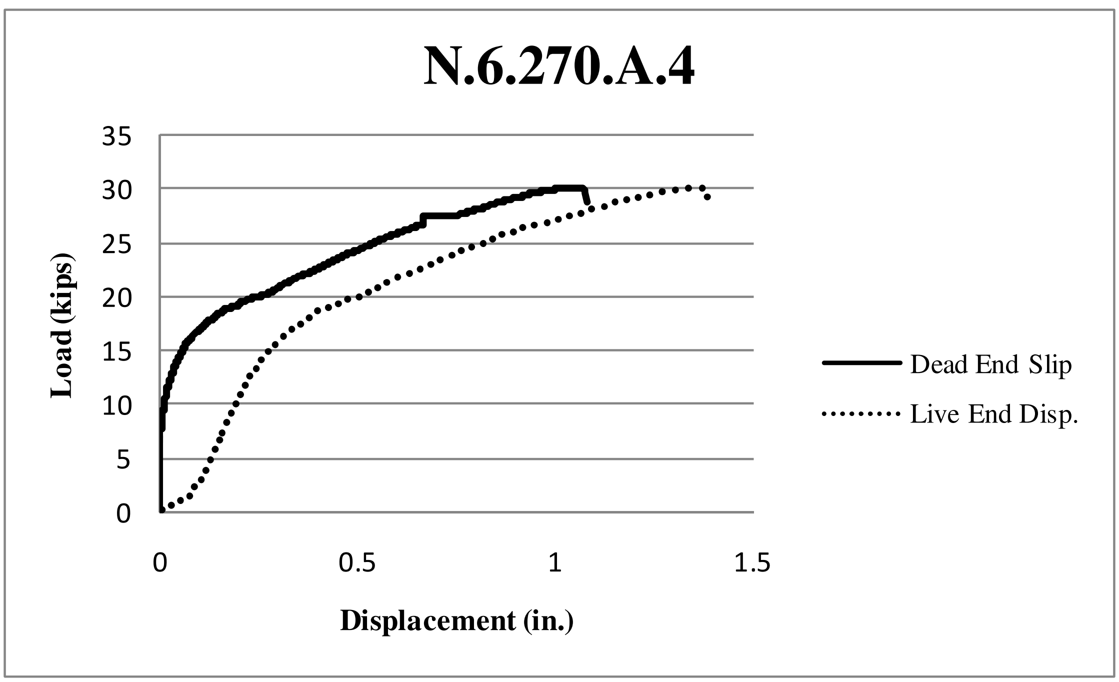

Figure B.34 Load vs. Displacement for N.6.270.A.4

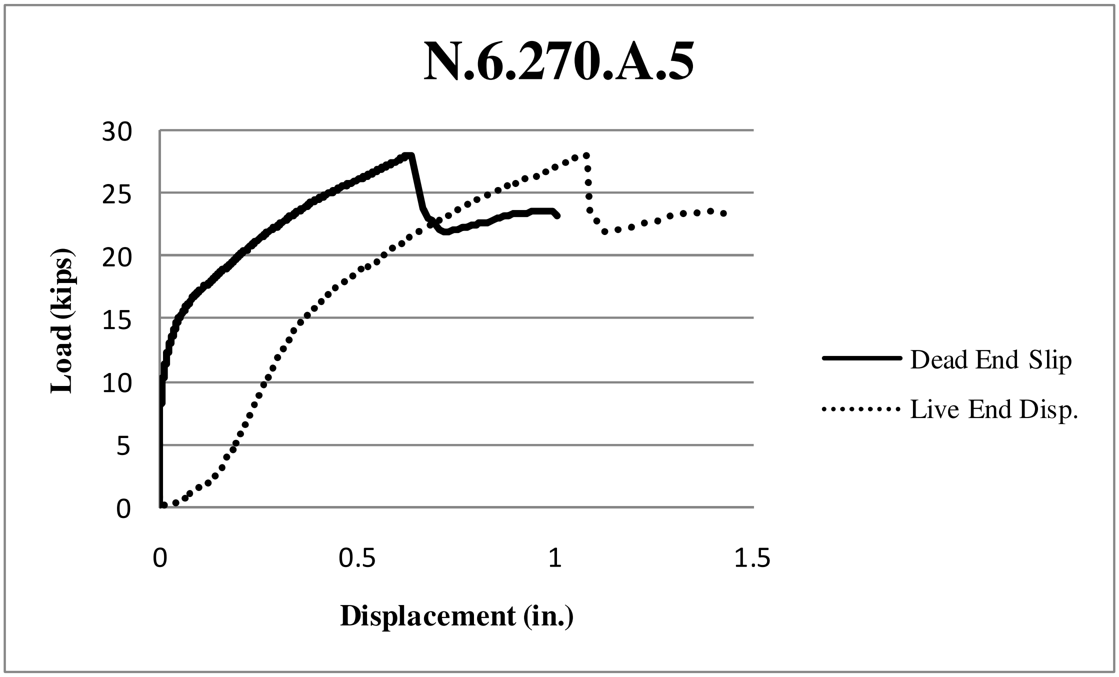

Figure B.35 Load vs. Displacement for N.6.270.A.5

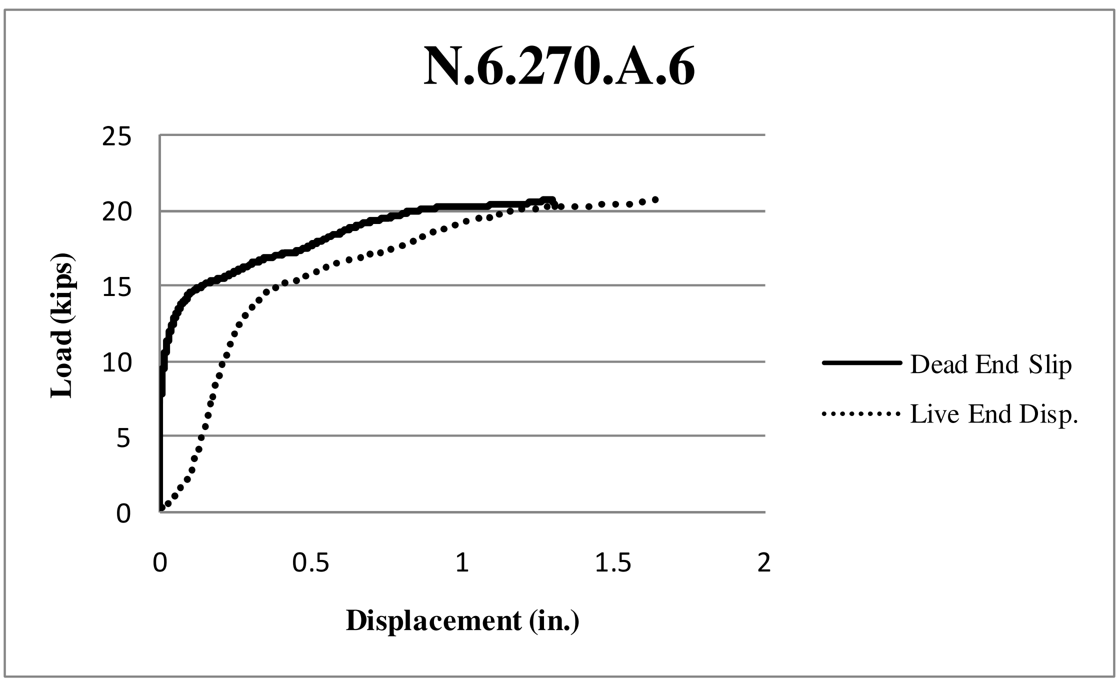

Figure B.36 Load vs. Displacement for N.6.270.A.6