MATERIAL PROPERTIES OF THE GRADE 300 AND GRADE 270 PRESTRESSING STRANDS AND THEIR IMPACT ON THE DESIGN OF BRIDGES

by

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(ABSTRACT)

The primary objective of this thesis was to test the material properties of the new Grade 300, low-relaxation prestressing strand. The purpose of this testing was to verify the advertised breaking strengths and relaxation properties of the Grade 300 strand. Additional properties, such as yield strength, modulus of elasticity, and elongation, were also examined. Several tests were performed on each specific type of strand. For example, six tension and eight relaxation tests were performed on the Grade 300, 0.5 in. diameter, 0.153 square in. area strand. From the tests, it is concluded that the advertised breaking strengths and relaxation properties from Strand-Tech Martin, Inc. were accurate and meet the industry standards for low relaxation strand.

The secondary objective of this project was to comment on the benefits of the Grade 300 strand as it pertains to the bridge industry. It was concluded from the tests that the Grade 300 strand had a 10 per cent larger 1 per cent elongation stress compared to the bridge industry standard Grade 270 strand. Furthermore, the amount of loss due to relaxation for the Grade 300 strand was comparative to that of the Grade 270 strand. While additional testing needs to be done to include stress-corrosion, transfer length, development length, and flexural strength, the completed testing indicates that less strand

will be required using Grade 300 strand versus Grade 270 strand to achieve a set span length and transverse girder spacing. In addition, with the industry gradually progressing toward using higher strength concretes, longer span lengths and larger transverse girder spacing can be achieved by using the Grade 300 higher strength strand.

The final objective of this testing was to examine the procedures and testing methods outlined by ASTM A416, *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete* (2005), ASTM E328, *Standard Test Methods for Stress Relaxation for Materials and Structures* (2002), and ASTM A370, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products* (2005). The breaking strength and yield strength tables in ASTM A416 (2005) need to be updated with the new Grade 300 strand information. Based on this testing, ASTM should also remove the recommendation of simply using aluminum foil and Standard V-Grips to grip the strand. Even though the standard Grade 270 and Grade 300 regular diameter strand met the material property requirements when using aluminum foil as a cushioning material, none of these samples broke clearly within the gage length of the strand. Furthermore, all of the super area strand samples failed prematurely at the grips due to the notching effect of the V-grip teeth. Thus, an alternative method involving aluminum tubing, aluminum oxide, and epoxy were used to create a cushioning device between the V-grip and the strand in order to achieve the true ultimate breaking stress of the strand. Finally, ASTM should comment on the impact of test length on the total relaxation measurements. Three test lengths were evaluated during the 26 relaxation tests. As the test length increased, the total measured relaxation decreased. Losses due to chuck slip and frame settlement were negligible as the strand test length increased.

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CHAPTER I
INTRODUCTION

1.1: Background

Success or victory is usually achieved through being or creating something stronger, faster, lighter, or cheaper. Eugene Freyssinet, a renowned French Army engineer, realized this in the early part of the 20^{th} century as one of the true pioneers of prestressed concrete. There were significant demands to produce a large number of beams in a very short period of time, and emergency prestressed concrete bridge beams served as a solution during the early part of World War II. Other wartime uses included railway ties and pillars for bomb-proof bunkers (Burns 2005). Freyssinet realized the value of using steel at a time period where there were limited resources due to the aftermath of the war. Prestressed concrete allowed designers to achieve longer span lengths, offset deflections, and limit concrete cracking. The myriad of possibilities for design that pouring concrete around high tensioned steel cables provided led to its use in the design and construction of both buildings and bridges. It first became popular in the United States with the construction of the 160 ft. span Walnut Lane Memorial Bridge in Philadelphia, Pennsylvania, in 1950. Engineering firms continue to pursue the stronger and more efficient bridge. Transportation departments continue to find ways to cut back, save money, and conserve materials and resources. The bottom line is that every firm, industry, and government continues to ask and look for ways to do more with less (Nilson 1987).

The bridge industry has looked to precast, prestressed concrete to optimize design and limit deflections. Standard I-beams and T-beams are mass-produced and make up a significant amount of new construction. The mass-production of these beams decreases the cost of labor significantly. Strand-Tech Martin, Inc., one of the new companies in the prestressed concrete industry, realized innovation in creating a stronger strand. With a production capacity of 60,000 tons of strand per year, their innovation led them to create and produce the latest strand on the market, the Grade 300 strand (www.strandtech.com).

The concept behind prestressing concrete is to introduce sufficient axial precompression in a beam to eliminate the tension in the concrete at service load. With concrete very strong in compression and weak in tension, engineers have the ability to prestress the concrete to their desired amount, achieving the degree of cracking, if any, they desire. Grade 270 strand has primarily been the bridge industry standard choice of strand for quite some time. The Grade 270 signifies strand with a guaranteed ultimate breaking stress of 270 ksi. Therefore, for a typical 0.5 in. diameter, 0.153 square in. area strand, the breaking strength is 270 ksi times 0.153 square in., or 40.5 kips. In comparison, the Grade 300, 0.5 in. diameter, super strand has a cross-sectional area of 0.167 square in. Therefore, its breaking strength is 300 ksi times 0.167 square in., or 50.1 kips. The Grade 270, 0.5 in. diameter, regular strand would actually reach its breaking strength before the Grade 300, 0.5 in. diameter, super strand would even reach yield. This kind of additional strength would be an advantage to innovative engineers, looking for a way to reduce material, labor, and cost.

There are other properties of the strand that would be of importance before an engineer would choose it for design. Prestress losses are often estimated in everyday projects. Estimated losses can be conservative to varying degrees. Actual calculated prestress loss less than an estimated loss assumption can save the engineer a few strands per girder. This is why it behooves the engineer to calculate prestress losses for larger projects. The jacking tension, P_j, which is the initial jacking force applied to the tendon, reduces to an initial prestress force, P_i. These instantaneous losses are due to friction between the strand and the conduit (post tensioning only), the strand slipping before it truly grabs, and elastic shortening of the concrete. Supplementary losses occur over time, and become negligible over a period of about one year. These losses reduce the initial prestress force to an effective prestress force, P_e. Creep of concrete due to sustained compression load over time, the shrinkage of concrete due to moisture loss, and the reduction in the steel strand stress at constant length are all interdependent. With the industry standard between 2.5 and 3.5 per cent loss due to relaxation, it was also necessary to explore the relaxation properties of the super and Grade 300 strands in comparison with the industry standard Grade 270 strand (Nilson 1987).

The ASTM has published specific procedures and recommended practices to test prestressing strand. ASTM A416 (2005), *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete*, outlines the ordering information, materials and manufacture information, mechanical properties, and dimensions and permissible variations of the low-relaxation Grade 250 and Grade 270 strands. ASTM A370 (2005) Appendix A7, *Method of Testing Multi-Wire Strand for Prestressed Concrete*, covers the general precautions, gripping devices, specimen preparation and the procedures for testing prestressing steel strands. ASTM E328 (2002), *Standard Test Methods for Stress Relaxation for Materials and Structures*, discusses relaxation testing for materials under constant constraint and environment. With new strands out on the market, it is imperative to find where the ASTM standards need to be modified. Considering that an ASTM Committee will usually revise an ASTM standard only once every five years, it is important to forward recommended changes to the committee quickly in the hopes of saving engineers time and money.

1.2 Objectives

1.2.1: Objective One

The primary objective of this project is to test the material properties of the latest prestressing strand out on the market. Within this scope, it will be determined if the 1 per cent elongation load, breaking strength, modulus of elasticity and steel relaxation of the Grade 300 strand will perform as required by ASTM to be qualified as ASTM A416 strand reinforcement.

To accomplish this objective, tests were conducted in the Virginia Tech Structures and Materials Laboratory. These tests consisted of steel relaxation tests in accordance with ASTM E328 (2002) and tensile tests in accordance with ASTM A416 (2005) and ASTM A370 (2005). In order to conduct both the tension and steel relaxation tests, a number of tests were conducted with the Grade 270, 0.5 in. diameter, 0.153 square in. area strand as a control to ensure the test setups and procedures were appropriate. The 30 tension tests and 26 relaxation tests conducted are outlined in the test matrix below.

Table 1.1: Test Matrix of Research

Strand Types	Strand Samples Tested				
Grade of Strand	GR 270	GR 270	GR 270	GR 300	GR 300
Diameter Strand (in.)	0.5	0.5	0.6	0.5	0.5
Area of Strand (in.^{2})	0.153	0.167	0.217	0.153	0.167
Type of Test Conducted	**Number of Tests Conducted**				
Relaxation	8	3	4	8	3
Ultimate Stress	6	5	7	6	6
Yield Stress	6	5	7	6	6
Modulus of Elasticity	6	5	7	6	6
Elongation	6	5	7	6	6

1.2.2: Objective Two

The secondary objective of the project is to comment on the advantages that the super and Grade 300 strands can have on the design of bridges. To accomplish this objective, the results from objective one testing were applied to the current AASHTO LRFD Bridge Design Specification, the Standard Specifications for Highway Bridges, and the Bulb-T Preliminary Design Tables. All of the design guidelines, tables, and charts were reviewed and recommended changes were made. Furthermore, as an example of the impact GR 300 strand can have on a bridge design, the Route 57 E.B.L. Bridge Design over the Dan River in Halifax County, Virginia was redesigned with the higher strength, larger diameter strand.

1.2.3: Objective Three

The third objective of the project is to review all of the ASTM requirements regarding the testing of prestressing strand. To accomplish this objective, application of the current ASTM standards to the testing of the new strand was followed. When the current ASTM standard did not work, alternative methods were used. All of the tables and charts within the current ASTM standards were reviewed and recommended changes were made.

1.3: Thesis Organization

Chapter 2 presents a literature review on the mechanical properties of the industry standard Grade 270 and Grade 250 low-relaxation strands as well as testing techniques and results that have worked in other research with regards to the Grade 300 strand. Chapter 3 presents all of the details about the test setup, instrumentation, and procedures for both the strand tension and strand relaxation testing. Chapter 4 focuses on answering the objectives and presents the results from every test that was conducted. This chapter includes a discussion of the findings with a thorough comparison to the theoretical data, insight into the impact of the Grade 300 and super strands on the bridge industry, and recommendations for LRFD, Standard Specification, and ASTM changes. Finally, in Chapter 5, an overall summary of the project to include the overall findings is presented with recommendations for further action to be taken.

CHAPTER II
LITERATURE REVIEW

2.1: What is Prestressed Concrete Strand?

Prestressing strand for concrete consists of seven wires, six of which are helically wrapped around one center wire. Each wire is drawn through nine tapered dies, which reduces the area of the wire by approximately 20 per cent and gives the individual steel rod its appropriate diameter. The wire consists of the same content as ordinary rebar, specifically carbon, manganese, phosphorus, sulfur, and silicon. However, there is slightly less iron (98 to 99 per cent) and more carbon (four to five times more) in the strand (Godfrey 1956).

The center straight wire of the seven-wire strand has a slightly larger diameter than the other six that surround it. For example, the larger center wire of a Grade 270, 0.5 in. diameter strand has a diameter approximately 0.007 in. larger than the outer wires (0.172 in. to 0.165 in.). In order to prevent slip of the helically wrapped rods, the outer wires are wrapped extremely tightly around the four percent thicker center wire (Podolney 1967). Prior to the stress-relieving process, the strand passes through machines to straighten the strand, making it easier to eventually place it into tension. The stress-relieving process burns off residual stresses caused by the drawing process, gives uniform stress within all seven wires, and most importantly makes the strand much more ductile. This process involves electrical induction at about 800 F, although the strand normally reaches about 600 F. Another important event during the stress-relieving process is stabilization. This thermo-mechanical process involves tensioning the strand between ridged drums or capstans. Imposing plastic strain (1 per cent permanent elongation) to the strand during the stress-relieving process produces the popular low-relaxation strand (Preston 1990). The hot and strained strand is water-cooled before it is dried and ready for use.

While Grade 250 and Grade 270 have been the main strands on the market since the 1950s, the Grade 300 strand is now available for consumers. In e-mail correspondence from Ronald Mann, sales and quality assurance representative from Strand Tech Martin, the makeup of the different grades of strand depends on a number of factors. Increased tensile strength (i.e., from Grade 270 to Grade 300) can be achieved during the drawing process (Mann, e-mail correspondence 2006). Strand producers can get greater tensile strength out of a wire by starting the drawing process with a larger area rod. For example, the rod used to develop 0.5 in. diameter, Grade 270 strand is typically 7/16 in. diameter, Grade 1080 steel.

One way to increase the guaranteed ultimate breaking stress of strand is to start out with a larger area rod, thus resulting in a greater reduction of area. Often, this process is combined with the choice to simply use rods of a higher tensile strength. Another technique to achieve a 300 ksi ultimate stress is to utilize additives such as vanadium to boost the tensile strength of a wire rod. Something to consider during the use of additives is the temperature at which the wire strand is being drawn. If special care isn't taken while drawing the wire through the tapered dies at high temperatures using additives, undesirable results occur, making the wire brittle.

Regardless of the method or combination of methods used to develop a specific grade of strand, the properties of the finished product can still be changed during the stabilizing process. Manufacturers control the temperature of the induction heaters and the tensioning between capstans to change the physical properties of the strand. Typically, increasing the tension of the strand and lowering the stabilization temperature will help increase a strand's tensile strength. In the end, the specific technique used depends on the technology, materials, and equipment available to the manufacturer.

2.2: Use of Prestressed Concrete

Generally, engineers use high strength concrete in combination with prestressing. The Design and Control of Concrete Mixtures (Kosmatka and Panarese 1994) defines high strength concrete as having a compressive strength of 6,000 psi or greater. The compressive strength of typical normal strength concretes range from 3,000 to 4,000 psi. The addition of superplasticizers and other admixtures to high strength concrete allows the cementitious mix to obtain the lowest practical water-cement ratio and void ratio (MacGregor 1992). Thus, high strength concrete is stronger and can handle greater force than normal strength concrete. As a result, the concrete cross-section does not have to be as large, and therefore can be more economical. Although these members are generally slender, the strands are stressed to ensure that cracks under service loads are minimized. High strength concrete also has a higher modulus of elasticity when compared to standard reinforced concrete. As a result, prestressing losses due to creep and elastic shortening are reduced.

There are a myriad of applications of prestressed concrete. The principles and techniques of prestressing are used in trusses, space frames, water storage towers, and nuclear containment vessels. The application discussed for purposes of this thesis pertains to its use in the design of bridges. Prestressed concrete is used in most bridge applications. In fact, a 1994 study by the Transportation Research Board (TRB)

Committee on Concrete Bridges chaired by Mary Lou Ralls from the Texas Department of Transportation indicated that prestressed concrete made up over 50 per cent of all bridges built, followed by steel and concrete bridges, both under 25 per cent (1994). Uses include railway, pedestrian, short span structures, and cable-stayed, continuous box girders with clear spans several hundred feet.

Standard sections in the design of most typical medium span bridges include AASHTO-PCI girders and bulb-tee girders (PCI, 1999). Both the AASHTO-PCI and the bulb-tee girders offer the bridge designer economical sections. The AASHTO-PCI sections were considered the standard in most states by the late 1950s. The Federal Highway Administration's funded study in the 1970s to find the most economical section resulted in the development of the bulb-tee sections. According to the TRB Committee on Concrete Bridges, the results from the study revealed that bulb-tee sections were actually up to 17 per cent more cost efficient and up to 35 per cent lighter when compared to the standard AASHTO sections (Committee on Concrete Bridges 1994). The efficient and popular standard sections on the market today are the Bulb-Tee girders, which have generally taken over for the older, but still relevant, AASHTO-PCI sections.

2.3: Testing Techniques and Procedures

Several engineers have outlined some of the essential testing techniques and procedures to use when testing prestressing strand. Many have specifically elaborated on the prominent problem of strand breaking prematurely during tension tests. The metallic properties and twisted wire arrangement tend to cause problems in the grips of the tension machine. The excessive bearing and pressure at very specific points on the strand where held by the gripping devices, may cause a premature grip failure of the strand. In accordance with ASTM A416 (2005), any test that fails prior to the minimum breaking strength is considered invalid and subject to retest. While ASTM A370 (2005) does provide a list of recommended gripping materials, many researchers have attempted to discover other methods to achieve clear breaks.

H. Kent Preston's (1985) recommendations included the use of the PLP Grip, the Sand Grip, the Tinius Olsen Grip, and the Aluminum Insert. The PLP Grip involves cementing a set of wires around the strand and using a piece of 50 grit carborundum cloth between the V-grips of the testing machine and the PLP Grip. While the PLP splices are no longer manufactured, the Florida Wire and Cable Company manufactures a FLO-LOC strand grip system. This system involves using two groups of five helical wires interwoven around the strand to be tested. The Sand Grip involves using aluminum U-grips with no teeth, lined with either a gritty mixture of sand and oil (SAE-10 or SAE-20) or 80 grit aluminum oxide and water to surround the strand. The Tinius Olsen Company manufactures a grip with a toothless liner. This grip actually requires no special preparation prior to tensioning the strand. The Aluminum Insert method uses aluminum angles lined with grease and a mixture of epoxy compound with sand or grit to surround the strand.

Chandu V. Shenoy and Gregory C. Frantz (1991) also researched a method to grip a strand and achieve reliable results during a tension test. In their paper, they reiterate the difficulty of conducting accurate tension tests on prestressing strand. They point out a number of potential problem areas including the strand characteristics, the common standard testing machine, cost and effort. During introductory testing, they detected some slippage at relatively low loads during the tension test using the FLO-LOC sleeves from the Florida Wire and Cable Company method. Their modified method involved applying an initial load of 5 kips and then attaching standard prestressing chucks on both ends of the strand outside the 4 in. V-grips. The 5 kip load was below the 7 kip load they found to be the load at which slip occurred using the FLO-LOC sleeves during preliminary testing. They found this method to be very effective, as the chucks prevented the strand from slipping through the sleeve, and the sleeve prevented the grips from digging into the strand. The chucks also provided additional resistance to assist in the sleeve and V-grip combination.

2.4: Prestressing Strand Stress versus Strain Behavior

Stranded cable of multiple sizes is available on the market. The most common size and type used is the Grade 270, 0.5 in. diameter strand. The mechanical properties of strand have been studied throughout its history, dating to the 1950s. A few articles written on the subject include: "The Physical Properties and Methods of Testing Prestressed Concrete Wire and Strand" (Godfrey 1956), "A Simple Method of Gripping Prestressing Strands for Tension Tests" (Shenoy and Frantz 1991), and "Stress-Strain Modeling of 270 ksi Low-Relaxation Prestressing Strands" (Devalapura and Tadros 1992). Properties such as ultimate strength, yield strength, ductility, and strain hardening have been published.

There are differences between the stress-strain curves of typical prestressing strand when compared to typical reinforcing steel. Figure 2.1 shows a typical stress versus strain plot for Grade 60 reinforcing steel. The curve shows a distinct upper yield point. In the elastic range, the specimen can be unloaded without any permanent deformation. Beyond the clearly defined yield point, the stress stays relatively constant while the strain increases. The plastic range is where permanent deformation takes place. Under further loading, the specimen undergoes strain hardening until it necks and fracture occurs.

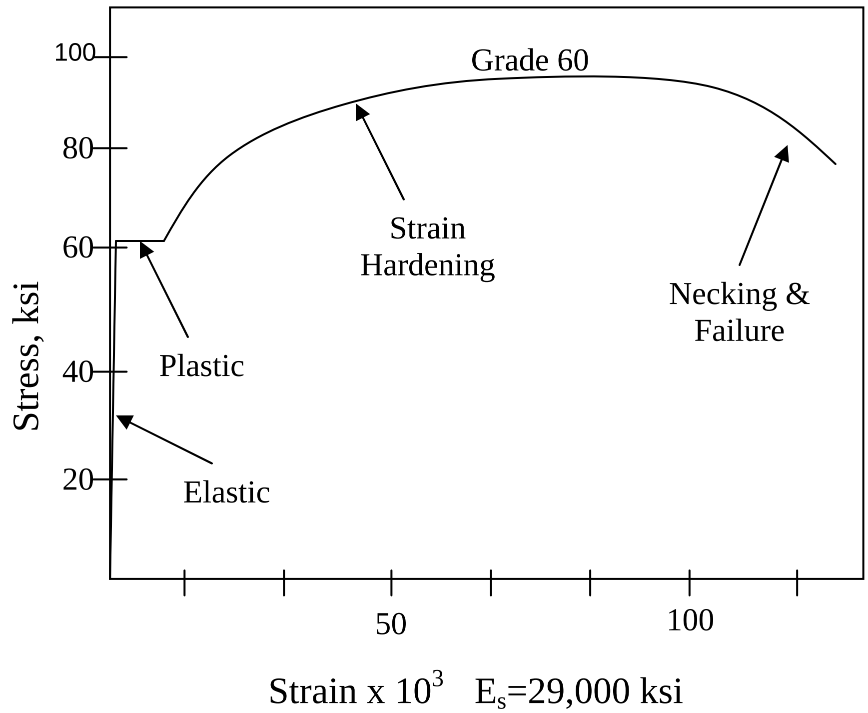

Figure 2.1: Stress-Strain Curve for Typical Steel Reinforcing Bar

A typical stress versus strain curve for prestressing strand is shown in Figure 2.2. Note that there is no distinct yield point for prestressing strand. The 1 per cent extension method or 0.2 per cent offset method is commonly used to define the yield point from a tensile test. The yield stress is significantly higher than that of typical steel. For example, Grade 60 reinforcing bar (shown in Figure 2.1) has a yield stress of 60 ksi which is less than one-quarter that of a typical GR 270, 0.5 in. diameter strand (yield stress of 243 ksi). Once the yield stress is reached, the slope of the stress-strain curve gradually flattens into the strain-hardening region before it fractures. In addition, the slope of the elastic region, or modulus of elasticity of strand, is generally lower (28,500 ksi) than that of typical steel (29,000 ksi). This is because the wound strand will slightly straighten as it is pulled in tension, resulting in more strain than in a typical steel coupon.

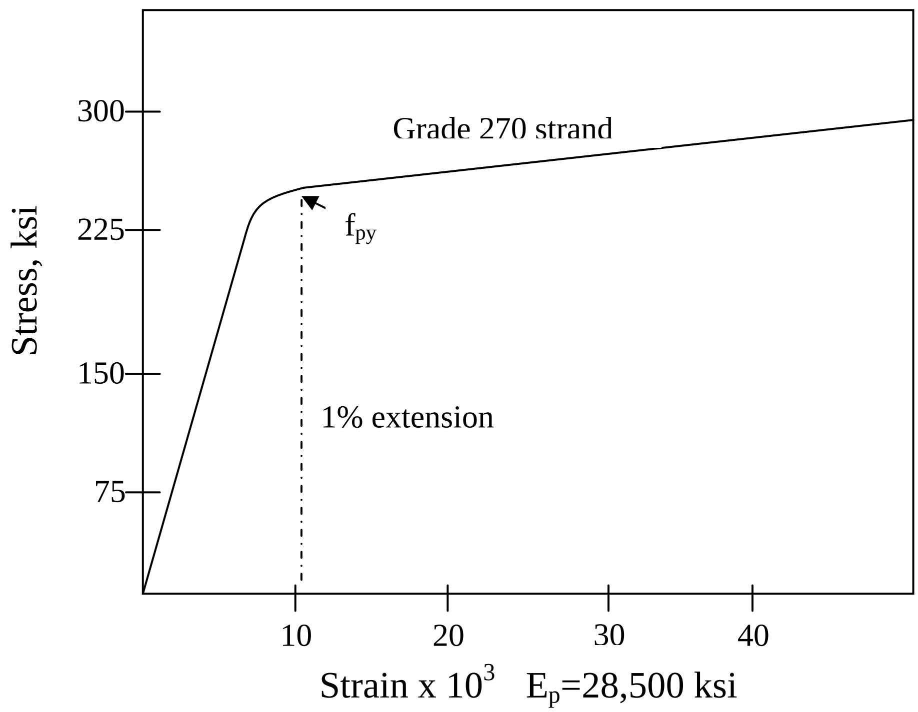

Figure 2.2: Stress-Strain Curve for Typical Prestressing Strand

H. J. Godfrey (1956) conducted tensile tests using file face grips on Grade 250, 3/8 in. diameter strand using different testing machines and grip lengths. While all the strand met the required breaking strength of 20,000 pounds as indicated in Table 2.1, he concluded that the length of the grips had an important role in the outcome of the tensile testing. The strand tested with shorter grips ended up breaking earlier, with shear type failures at the edge of the grips. The strand tested with longer grips broke within the gage length in a tensile type of failure.

Table 2.1: Tensile Tests from H.J. Godfrey

Tensile Tests, Grade 250, 3/8" Diameter, 0.080 in^2 Area				
Test No.	**Grip Length (in)**	**Actual Strength (lb)**	**Elongation %**	**Fracture Type**
1	2.5	20,400	2.4	Shear, one wire, at grip
2	3.75	21,950	6.7	Tensile, all wires, at grip
3	4.25	21,800	8.0	Tensile, all wires, between grips

Shenoy and Frantz (1991) conducted 12 tension tests on strand removed from an old bridge beam. Six of the tests were conducted on 0.5 in. diameter, Grade 270 strand, and the other six were on 7/16 in. diameter, Grade 250 strand.   The testing involved several different techniques to grip the strand. The methods used on the first five tests resulted in negative results; even the sixth test with their preferred method of using chucks and sleeves for grips was very close (41.0 kips breaking strength versus 41.3 for a nominal area of 0.153 square in.). Tests seven through nine involved the use of their developed modified procedure, using the FLO-LOC sleeves between V-grips and chucks on the ends to help prevent slip and share the load. Tests 10 through 12 were conducted by the Florida Wire and Cable Company with their specialized testing equipment. Tests 6 through 12 all met the minimum required breaking strength. A summary of the tension tests conducted by Shenoy and Frantz (1991) is displayed in Table 2.2.

Table 2.2: Tensile Tests from Shenoy and Frantz

Test #	Strand	Ultimate Nominal Stress (ksi)	Grip Type	Failure Type
1	GR 270, 1/2", 0.153 in^2	256	V-grips only	In the grips
2	GR 270, 1/2", 0.153 in^2	229	Chucks only	In the chuck jaw
3	GR 270, 1/2", 0.153 in^2	225	V-grips and Chucks	In the chuck jaw
4	GR 270, 1/2", 0.153 in^2	260	V-grips, Chucks, 12" sleeves	Inside sleeve, outside grips
5	GR 270, 1/2", 0.153 in^2	267	V-grips, Chucks, 14" sleeves	5 wires in center, 2 wires inside sleeve
6	GR 270, 1/2", 0.153 in^2	268	V-grips, Chucks, 20" sleeves	Clean break middle
7	GR 250, 7/16", 0.108 in^2	264	V-grips, Chucks, 20" sleeves	Clean break middle
8	GR 250, 7/16", 0.108 in^2	262	V-grips, Chucks, 17" sleeves	Clean break middle
9	GR 250, 7/16", 0.108 in^2	265	V-grips, Chucks, 14.5" sleeves	Clean break middle
10	GR 250, 7/16", 0.108 in^2	264	Florida Wire and Cable	Not available
11	GR 250, 7/16", 0.108 in^2	261	Florida Wire and Cable	Not available
12	GR 250, 7/16", 0.108 in^2	264	Florida Wire and Cable	Not available

2.5: Steel Relaxation of Prestressing Strands

Strand exhibits its mechanical property of relaxation by losing tensile stress when stressed and held at a constant length. The relaxation properties of strand primarily depend on the method used to manufacture it. Six wires are wrapped around the center seventh wire. Stress-relieved strand is made by heating the strand to between 600 F and

700 F and then cooling it slowly. The helically wrapped strand is considered low-relaxation when it undergoes tensioning during the heating process. The significant difference between stress-relieved strand and low-relaxation strand as far as relaxation properties are concerned is evident in Figures 2.3 and 2.4. Nilson (1987) provides the results of analysis from numerous stress-relieved relaxation tests in Figure 2.3.

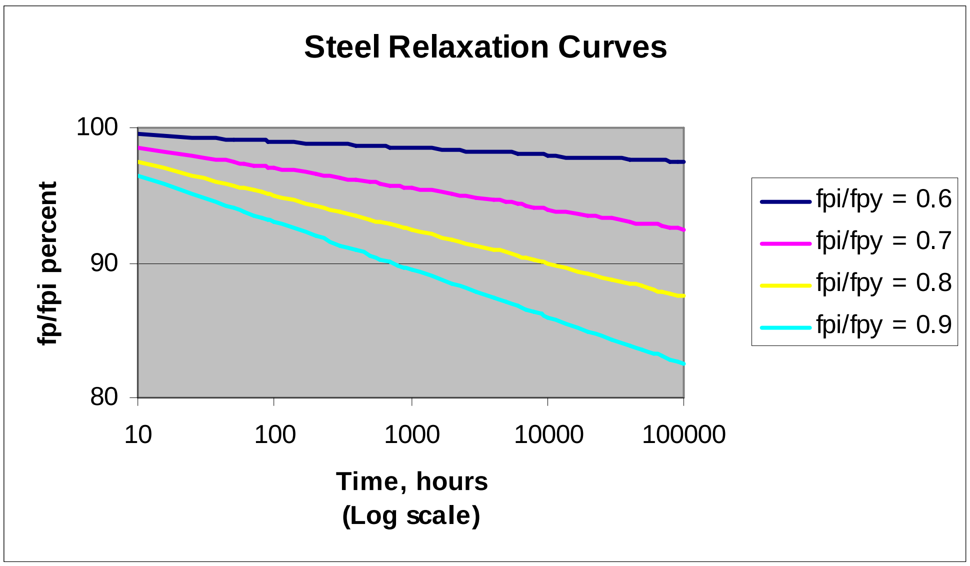

Figure 2.3: Typical Relaxation Curves for Stress-Relieved Strand

The curves can be approximated using Equation 2.1. The equation was originally published in "A Study of Stress Relaxation in Prestressing Reinforcement" (Magura, et al. 1964) and later adopted and published in a PCI Committee report "Recommendations for Estimating Prestress Losses" (1975).

$$\frac{f_p}{f_{pi}} = 1 - (\frac{\log t}{10})(\frac{f_{pi}}{f_{py}} - 0.55) \qquad \textbf{(2.1)}$$

where:

f_p = stress in strand at time t (ksi)

f_{pi} = jacking stress (ksi)

t = time (hours)

f_{py} = specified yield stress for strand (ksi)

Similarly, relaxation curves for low-relaxation strand are shown in Figure 2.4.

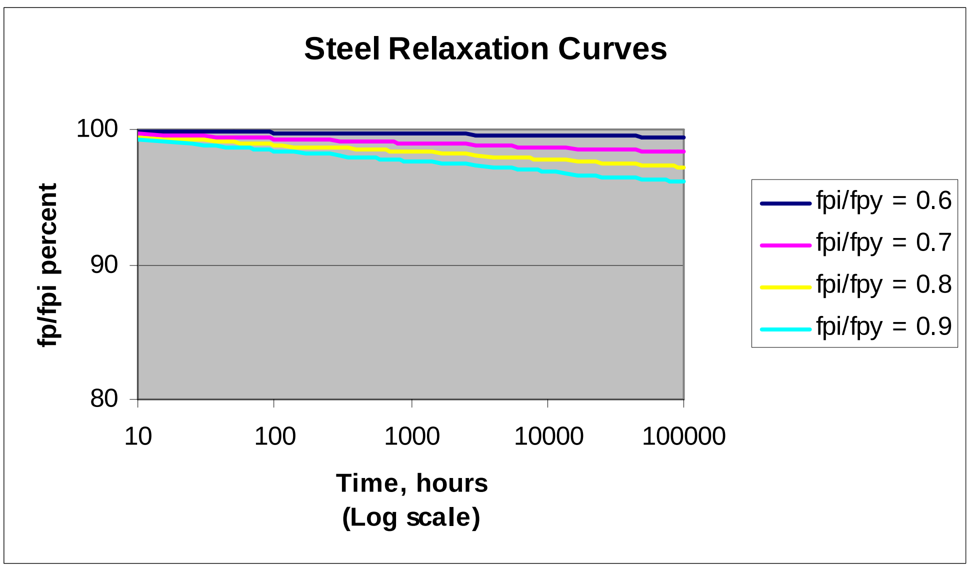

Figure 2.4: Typical Relaxation Curve for Low-Relaxation Strand

Originally based on the work of Magura et al. (1964), these curves are generated using Equation 2.2, modified from Equation 2.1 to account for the behavior of low-relaxation strand as listed in the PCI Committee report "Recommendations for Estimating Prestress Losses" (1975).

$$\frac{f_p}{f_{pi}} = 1 - (\frac{\log t}{45})(\frac{f_{pi}}{f_{py}} - 0.55) \qquad \textbf{(2.2)}$$

where:

f_p = stress in strand at time t (ksi)

f_{pi} = jacking stress (ksi)

t = time (hours)

f_{py} = specified yield stress for strand (ksi)

As demonstrated from Figures 2.3 and 2.4, the amount of steel relaxation loss for a low-relaxation strand is about 25 to 30 per cent that of the stress-relieved strand. The PCI Design Handbook (1999) adopted its relaxation loss equations from “Estimating Prestress Losses” (Zia, et al. 1979) as shown in Equation 2.3.

$$RE = [K_{RE} - J(SH + CR + ES)]C \qquad \textbf{(2.3)}$$

where:

RE = relaxation of tendons (psi)

K_{RE} = 20,000 psi for Grade 270 stress-relieved; 5,000 psi for Grade 270 low-relaxation

J = 0.15 for Grade 270 stress-relieved; 0.04 for Grade 270 low-relaxation

$C_{(fpi/fpu\ =\ 0.75\ (typical))}$ = 1.45 for GR 270 stress-relieved; 1.00 for GR 270 low-relaxation

SH = shrinkage of concrete (psi)

CR = creep of concrete (psi)

ES = elastic shortening (psi)

The 17th Edition, Standard Specification for Highway Bridges utilizes the same philosophy for estimating stress-relieved and low-relaxation losses as demonstrated in Equations 2.4 and 2.5, respectively (AASHTO 2002).

$$CR_S = 20{,}000 - 0.4ES - 0.2(SH + CR_C) \qquad \textbf{(2.4)}$$

$$CR_S = 5{,}000 - 0.1ES - 0.05(SH + CR_C) \qquad \textbf{(2.5)}$$

where:

CR_S = steel relaxation (psi)

SH = shrinkage of concrete (psi)

CR_C = creep of concrete (psi)

ES = elastic shortening (psi)

ACI 318 (2002) points to "Recommendations for Estimating Prestress Losses" (1975) and "Estimating Prestress Losses" (Zia, et al. 1979) in order to develop reasonable estimates for prestress loss. Regardless of the equation used, the curves from Figures 2.3 and 2.4 indicate that relaxation is a function of time. While the majority of the losses occur over the first 100 hours, these losses occur indefinitely. According to ASTMs A416 (2005) and E328 (2002), low-relaxation strand shall not exhibit more than 3.5 per cent relaxation when stressed to 80 per cent of the tensile strength and not more than 2.5 per cent relaxation when stressed to 70 per cent.

2.6 Interaction of Steel Relaxation and Other Losses

As demonstrated in Equations 2.3, 2.4, and 2.5, relaxation, creep, and shrinkage losses are interdependent. Often times, many of the factors affecting relaxation are unknown at the design stage. Assuming normal temperatures, AASHTO LRFD (2004) and NCHRP 496: Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders (2003) use Equation 2.6, which is a slight modification conservative to Equation 2.2 in that it has a denominator of 40 in lieu of 45.

$$\Delta f_{pR1} = \frac{\log(24.0t)}{40}\left[\frac{f_{pj}}{f_{py}} - 0.55\right] f_{pj} \text{ (ksi)} \qquad \textbf{(2.6)}$$

where:

t = time (days)

f_{pj} = initial jacking stress (ksi)

f_{py} = prestressing strand yield stress (ksi)

In estimating pretension losses for low-relaxation strand after transfer, AASHTO LRFD (2004) uses Equation 2.7, and the NCHRP 496: Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders (2003) uses Equation 2.8.

$$\Delta f_{pR2} = 0.3\lfloor 20.0 - 0.4\Delta f_{pES} - 0.2(\Delta f_{pSR} + \Delta f_{pCR})\rfloor \text{ (ksi)} \qquad \textbf{(2.7)}$$

$$\Delta f_{pR2} = 6 - 12.0\Delta f_{pES} - 0.6(\Delta f_{pSR} + \Delta f_{pCR}) \text{ (ksi)} \qquad \textbf{(2.8)}$$

where:

f_{pES} = loss due to elastic shortening (ksi)

f_{pSR} = loss due to shrinkage (ksi)

f_{pCR} = loss due to creep of concrete (ksi)

In the event that a designer does not have access to this data, AASHTO LRFD (2004) assumes the loss to be 3.0 ksi.

Unlike the AASHTO LRFD (2004), the Interim 2005 AASHTO LRFD (2005) defines total relaxation as the sum of relaxation from transfer until the time of deck placement and relaxation after deck placement. Relaxation losses prior to transfer are said to be compensated by the typical slight overjacking when stressing the strands. While the AASHTO LRFD (2005) allows a designer to use 2.5 ksi as a low-relaxation strand relaxation loss estimate for standard precast, pretensioned members (AASHTO LRFD 5.9.5.3), a more accurate estimation is found by using Equations 2.9 and 2.10.

$$\Delta f_{pR1} = \left[\frac{f_{pt}}{K'_L} \frac{\log(24t)}{\log(24t_i)} \left(\frac{f_{pt}}{f_{py}} - 0.55 \right) \right] \left[1 - \frac{3(\Delta f_{pSR} + \Delta f_{pCR})}{f_{pt}} \right] K_{id} \text{ (ksi)} \qquad \textbf{(2.9)}$$

$$\Delta f_{pR2} = \Delta f_{pR1} \text{ (ksi)} \qquad \textbf{(2.10)}$$

where:

Δf_{pR1} = prestress loss due to relaxation between time of transfer and deck placement (ksi)

f_{pt} = stress in strands immediately after transfer, greater than or equal to 0.55 f_{py} (ksi)

K'_L = type of steel factor: 45 for low-relaxation, 10 for stress-relieved

t = time between strand tensioning and deck placement; typically assumed 120 days

t_i = time between strand tensioning and transfer; typically assumed 0.75 days

f_{py} = yield stress of the strand (ksi)

Δf_{pSR} = loss due to shrinkage of concrete (ksi)

Δf_{pCR} = loss due to creep of concrete (ksi)

K_{id} = factor for restraint of concrete caused by bonded reinforcement; typically 0.8

Δf_{pR1} = prestress loss due to relaxation between time of transfer and deck placement (ksi)

Δf_{pR2} = prestress loss due to relaxation after time of deck placement

The term in the first square brackets from Equation 2.9 can stand alone as relaxation without creep and shrinkage effects (AASHTO LRFD Interim 2005 C5.9.5.4.2c-1). Equation 2.10 is based on research indicating that the relaxation losses before deck placement are approximately equal to relaxation losses afterwards (AASHTO LRFD Interim 2005 5.9.5.4.3c-1).

These design equations rely on a number of factors, with the primary factor being temperature. Relaxation losses increase as the temperature increases (AASHTO LRFD Interim 2005 5.9.5.4.2c). Creep and shrinkage of the concrete cause the strand to shorten and reduce the relaxation of the strand. Steel relaxation is further reduced by the transformed section coefficient K_{id}, which accounts for the restraint in the concrete member caused by bonded reinforcement. Typically taken as 0.8, this factor also reduces the relaxation estimate at transfer.

Arcady V. Koretsky and Ross W. Pritchard (1982) conducted relaxation testing over a period of three years. They focused on the lack of a clear standard to conduct relaxation tests and their assertion that the codes should not neglect the first minute of testing. The authors tested both 0.5 in. diameter low-relaxation and normal relaxation strand. The tests ranged from 48 to just over 2,000 hours, and unlike ASTM A-416 (2005), the authors measured relaxation from the moment they reached their specified test load. Results from isothermal relaxation tests with strands stressed to 80 per cent of the breaking strength indicated that while total relaxation ranged between 1.41 per cent after the 48 hour test and 4.90 per cent after one of the 1,000 hour tests, the first minute of loss amounted to between 10 and 27 per cent of the total loss after 1,000 hours. The isothermal relaxation tests are summarized in Table 2.3.

As expected, the relaxation losses for normal relaxation strand were higher than the losses for low-relaxation strand. Furthermore, the losses for low-relaxation strand when stressed to 80 per cent of the breaking strength were generally below 3.5 per cent, required by ASTM A416.

Table 2.3: Summary of Isothermal Relaxation Tests by Koretsky and Pritchard

Test	Strand	Load Percent	Test Time (hours)	% Loss	% Loss After 1 Minute
1	Low-relaxation	80	1,000	3.16	2.36
2	Low-relaxation	80	200	2.90	2.41
3	Low-relaxation	80	170	4.90	3.90
4	Low-relaxation	80	142	4.35	3.76
5	Low-relaxation	80	560	4.32	3.36
6	Low-relaxation	80	1,000	4.80	3.68
7	Low-relaxation	80	1,000	3.60	3.12
8	Low-relaxation	75	1,000	3.55	3.19
9	Low-relaxation	75	1,000	3.35	2.63
10	Low-relaxation	70	1,000	2.14	2.14
11	Low-relaxation	70	961	2.94	2.30
12	Low-relaxation	50	48	1.41	0.99
13	Low-relaxation	80	343	4.05	2.97
14	Low-relaxation	70	1,000	2.15	1.85
15	Low-relaxation	80	144	3.50	2.75
16	Low-relaxation	70	2,069	1.90	1.39
17	Normal Relaxation	80	2,000	8.30	7.72
18	Normal Relaxation	80	1,000	7.60	6.78
19	Normal Relaxation	70	750	3.55	3.00
20	Normal Relaxation	50	48	1.07	0.57
21	Normal Relaxation	80	1,000	9.80	8.42

A question remaining from this research was the impact that length had on the results of relaxation testing. International codes differed as to the recommended length of the test specimen (Koretsky and Pritchard 1982). For example, they point out in the Standards Association of Australia AS 1311 "Steel Tendons for Prestressed Concrete" (1972), that the minimum test length is 100 strand diameters. The British Standards Institution states in the British Standards Institution BS 3617, "Standard Specification for Seven Wire Strand for Prestressed Concrete" (1971) that the minimum test length is 14 strand diameters. The Euro-International Committee for Concrete and International Federation for Prestressing (CEB-FIP) states in the "Model Code for Concrete Structures" (1978) that the standard minimum test length is 40 strand diameters. Meanwhile, the latest ASTM A416 (2005) states that the preferred test length is at least 60 times the strand diameter, although it is permitted to substitute a gage length of 40 times the strand diameter if necessary.

A study conducted at the University of Illinois in 1985 involved two series of tests dealing with steel relaxation properties (Buckler and Scribner 1985). The first series of tests involved strands that were stressed and monitored for 1,000 to 2,000 hours. In the second series of tests, strands were stressed, and then reduced 24 hours after the initial tensioning, before being monitored for the remainder of the test. From the first series of tests (the series relevant to this research), six low-relaxation strands were tested with an initially applied stress varying from 60 to 80 per cent of each strand's ultimate breaking stress. A summary of the data from the low-relaxation strands tested is shown in Table 2.4 (Buckler and Scribner 1985).

Table 2.4: Summary of Relaxation Tests by Buckler and Scribner

Ultimate Stress (ksi)	Yield Stress (ksi)	Initial Stress (ksi)	Length of Test (hours)	Initial Stress versus f_{pu} (%)	Initial Stress versus f_{py} (%)	Final Stress (ksi)	Relaxation (%)
287	266	162	1008	56.4%	60.9%	160	1.01%
287	266	176	1008	61.3%	66.2%	174	1.31%
287	266	189	1008	65.9%	71.1%	186	1.37%
287	266	189	1006	65.9%	71.1%	186	1.40%
287	266	203	1008	70.7%	76.3%	200	1.35%
287	266	216	2008	75.3%	81.2%	212	1.77%

From their studies, Buckler and Scribner (1985) concluded that the steel relaxation equation recommended by strand manufacturers at that time (see Equation 2.2) was unconservative. They felt that steel relaxation was best approximated using a quadratic function of the natural log of time as shown in Equation 2.10.

$$\%SR = A + B(\ln t) + C(\ln t)^2 \text{ (ksi)} \qquad \textbf{(2.10)}$$

where:

A = 1.97 x R – 1.0

B = 0.118 x R – 0.047

C = 0.040 x R - 0.014

R = ratio of initial stress to stress at 0.1 percent offset

2.7: Conclusions and Recommendations

From previous experimental data, it can be concluded that the Grade 250 and Grade 270 strands have played a pivotal role in the design and construction of bridges worldwide. However, many questions still remain. Some of the major questions include:

1) Will the Grade 300 strand perform as required by ASTM to be qualified as ASTM A416 strand reinforcement? Specifically, the requirements of ultimate strength, yield strength, elongation, and steel relaxation must be examined.

2) Does the length of strand tested play a role in the outcome of relaxation tests?

3) Will the gripping methods recommended by ASTM be sufficient to conduct tension tests for the super and Grade 300 strands?

4) Are modifications to the ASTM standards, AASHTO LRFD, and Bridge Design Specification recommended based on the outcomes of this research?

5) What impact would the Grade 300 strand have on the bridge industry?

There are several other questions with regards to the Grade 300 strand that must be answered, and more research in this area is warranted. The goal of this thesis is to answer all of the questions listed above.

CHAPTER III
TEST SETUP, INSTRUMENTATION AND PROCEDURES

3.1: Tension Tests

The goal of the tension tests was to find the yield strength, breaking strength, modulus of elasticity and elongation of the super and Grade 300 strands. In order to conduct the testing, ASTM A416 (2005) and A370 (2005) were the primary guidelines used to conduct all of the testing. While the ASTM standards cover both low-relaxation and stress-relieved (normal-relaxation) strand, the focus of this testing was on the industry standard low-relaxation strand.

In order to ensure that the testing was done correctly, preliminary testing was conducted on Grade 270, 0.5 in. diameter, 0.153 square in. area strand. Positive results during this preliminary testing provided confidence in the results of the testing since the material properties of minimum breaking strength and yield strength are listed in ASTM A416 (2005). The testing was then conducted on a number of other strands provided by Strand Tech Martin, Inc. While the primary objective was to test the material properties of the strand, the performance of two different grip methods was also evaluated. A summary of all tension testing meeting the ASTM minimum requirements is shown in Table 3.1 below. Regardless of the gripping procedures used to conduct tension testing, ASTM A370 (2005) Note A7.4 states that tests must meet the minimum guaranteed mechanical property values in order for the test to be considered valid. While the preferred result of breaking the strand is a clear break in the middle of the specimen, Note A7.4 (2005) points out that the strand can fracture in the jaws, and the test can be considered valid if it meets the minimum guaranteed mechanical property requirements.

Some of the testing conducted during this research with aluminum foil as a cushioning material resulted in breaks in the jaws with breaks premature to the guaranteed minimum ultimate breaking strength. These tests are noted with an asterisk in Table 3.1. Since this data was not considered valid, it was not saved or used in further analysis.

Table 3.1: Tension Testing Summary

Tension Testing Summary					
Type	**Diameter (in.)**	**Area ($in.^2$)**	**Material Properties**	**Aluminum Foil**	**Aluminum Angle & Aluminum Oxide**
GR 270	0.5	0.153	6	4	2
GR 300	0.5	0.153	6	4	2
GR 270	0.5	0.167	5	0*	5
GR 300	0.5	0.167	6	0*	6
GR 270	0.6	0.217	7	2*	5

* Indicates testing conducted that did not meet minimum requirements and therefore not saved or used in analysis.

3.1.1: Tension Test Setup

One of the most important aspects of the tension tests was to ensure that the extensometer was calibrated. The extensometer, as explained in further detail in Section 3.1.2, was pivotal for the calculation of strain, elongation, modulus of elasticity and yield strength. ASTM A416 (2005) states that the calibration must be done with the smallest division less than or equal to 0.0001 in./in. of gage length. The calibration results from the 2 in. extensometer used throughout the testing are displayed in Table 3.2.

Table 3.2: Extensometer Calibration Data

Actual Deflection (in.)	Actual Strain (in./in.)	Extensometer Reading (in./in.)	Calibration Factor
0.1	0.5000	0.0532	0.9407
0.2	0.1000	0.1065	0.9390
0.3	0.0150	0.1601	0.9369
0.4	0.2000	0.2137	0.9359
Final Calibration Factor Average			0.9381

The strand was sent from Strand Tech Martin, Inc. in various lengths. Each test specimen was cut using a Milwaukee Heavy Duty Bandsaw. ASTM A370 A7.4 (2005) warns against utilizing extreme high temperatures (over 700 F) on the strand, because it may result in a diminished ductility and strength. The abrasive saw shown in Figure 3.1 quickly cut through the strand with little to no heating observed. Actual strand testing lengths varied during the tension tests due to the lack of precision for actually gripping the strand in the universal SATEC machine. Strand was cut into approximately 50 in. lengths and was set in the grips with the hydraulic heads between 32 in. and 40 in. apart.

Figure 3.1: Milwaukee Heavy Duty Band Saw

ASTM A370 A7.2 (2005) warns that gripping devices may cause notching and cutting of the strand, resulting in a premature fracture of the strand at the grips. It is preferable for the strand to fracture between the grips in a clear break, where all of the individual wires break simultaneously. Numerous gripping devices are recommended by ASTM, largely due to the wide variety of tension testing machines on the market. V-grips are part of the equipment available for use to conduct this research. These V-grips are roughly equivalent to the Standard V-Grips with Serrated Teeth Using Cushioning Material described in ASTM A370 A7.3.3 (2005). While the number of teeth in the V-grips should be approximately 15 to 30 per in., the V-grips available for use for this research had 12 teeth per in. Nevertheless, the effective gripping length was 4 in., in accordance with the ASTM.

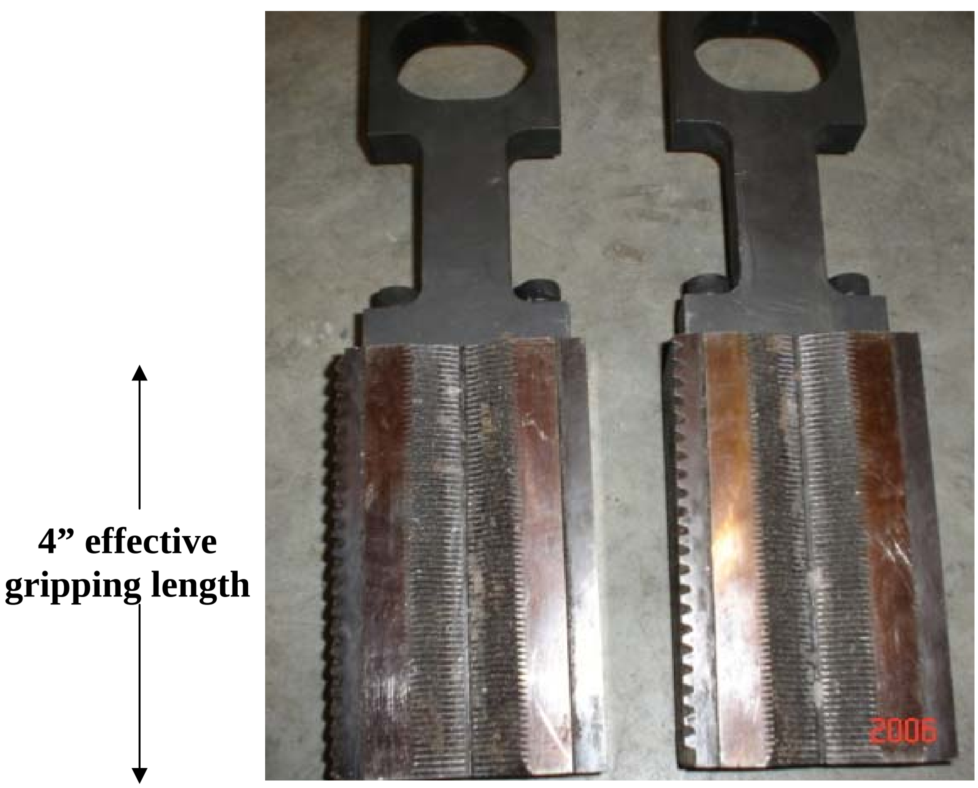

Figure 3.2: V-grips for Tension Tests

The first method involved the use of aluminum foil to cushion the strand between the grips. This method was used because the cushioning material recommended by ASTM includes aluminum foil, carborundum cloth, and bra shims. Approximately 24 in. of aluminum foil was wrapped multiple times around each end as shown in Figure 3.3 below. The foil covered 12 in. on each end of the strand piece to be tested. This ensured that the 4 in. grips of the SATEC machine would easily grip onto the cushioning aluminum foil. Carborundum cloth, lead foil, and bra shims were not used during this research. Their performance as cushioning material in gripping the Grade 300 and super strands is a possibility for future research.

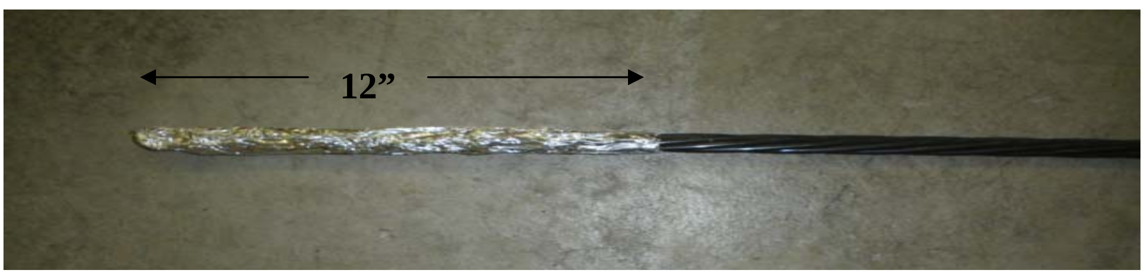

Figure 3.3: Aluminum Foil Cushioning Material

The second method used in this research for gripping the strand was very similar to the aluminum insert method. Recommended by Ronald Mann, quality assurance technician for Strand Tech Martin, Inc., and published by H. Kent Preston (1985), the aluminum insert method involves using aluminum insert angles, silicon carbide grit, and epoxy compound to surround the strand as cushioning material between the grips. For this research, 3/4 in. x 1/16 in. x 8 in. aluminum tubing was cut in half and trimmed.

Figure 3.4: Aluminum Round Tubing 3/4 in. x 1/16 in. x 8 in.

A sandy mixture was developed with 80 grit aluminum oxide and water. Prior to applying the gritty combination to the aluminum tubing, another mixture consisting of epoxy resin and fast hardener was mixed in to form a cohesive combination.

Figure 3.5: 80 Grit Aluminum Oxide

Once the grips were placed around an end of the strand, pressure was applied, and the mixture hardened overnight for testing the next day. During testing, the lateral force from the hydraulic grips left deep impressions along the length of the aluminum inserts as shown in Figure 3.6. Subsequent use would likely result in actual notching of the strand. As a result, the grips were never reused.

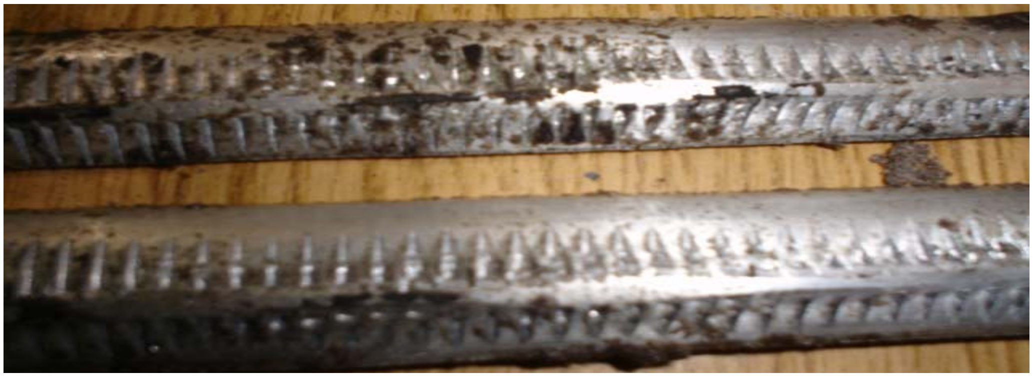

Figure 3.6: Aluminum Tube Inserts

3.1.2: Tension Test Instrumentation

The extensometer used for this research was a SE2-50 Extensometer with a 2 in. strain gage length shown in Figure 3.7. The extensometer measured displacements at mid-length of the test specimen. Output was provided as either strain (in./in.) or as displacement (in.). The knife-edges of the extensometer had a tendency to slip on the twisting strand. To minimize this, two-sided tape and multiple rubber bands were used to keep the extensometer straight and tight against the strand.

Figure 3.7: SE2-50 Extensometer with 2 in. Gage Length

ASTM also calls for the use of a 24 in. extensometer to measure elongation; however, an extensometer of this length was unavailable. Instead, output from the 2 in. extensometer until it was removed was added to output from the SATEC crosshead displacement to calculate total elongation. Early in the testing, an 11-13/16 in. extensometer was used parallel to the 2 in. extensometer, until it was damaged during a premature strand fracture. Results comparing the two extensometers and the elongation calculated from crosshead displacements are similar, as demonstrated in Table 3.3.

Table 3.3: Extensometer Output Comparison

Strand	Grade 300	Grade 300	Grade 270	Grade 270	Grade 270	Grade 270
Diameter (in.)	0.5	0.5	0.5	0.5	0.5	0.6
Area (in.^{2})	0.153	0.153	0.153	0.153	0.153	0.217
Test Number	1	2	1	2	3	1
Elongation measured with 2 in. Extensometer	6.9%	6.4%	6.4%	6.8%	6.9%	6.6%
Elongation measured with 11-13/16 in. Extensometer	6.9%	6.2%	6.3%	6.9%	6.6%	6.4%
Elongation from early crosshead displacement	7.2%	6.6%	6.7%	7.1%	7.2%	6.9%

The SATEC universal testing machine was updated in the Virginia Tech Structures and Materials Laboratory in the middle of the tension tests. The majority of the tests were conducted using the new MTS 407 controller connected to the SATEC universal testing machine. The equipment was calibrated by a certified technician before its use. The SATEC machine had hydraulically controlled grips in both the upper and lower crossheads. The MTS 407 controller enabled the crosshead to move at a constant rate until the specimen fractured or the test was terminated by the touch of the push-button MTS control panel shown in Figure 3.8.

Figure 3.8: MTS 407 Controller for Universal SATEC Machine

The data acquisition system shown in Figure 3.9 recorded data automatically every second. The data recorded included time, load (kips), crosshead movement (in.) and extensometer displacement (in.).

Figure 3.9: Data Acquisition System Scanners

3.1.3: Tension Test Procedures

Once the cut strand's grips were placed in the serrated teeth of the hydraulic SATEC grips, the 2 in. extensometer was secured to the strand. The crosshead was adjusted to ensure that the strand was straight and taut, with the MTS output reading zeroed. The speed of the testing varied, but was usually set at approximately 5 kips per minute. ASTM A370 (2005) states that the accurate load and displacement output should be the priority for determining the speed of testing. Limits on the speed of testing include a range between 10,000 and 100,000 psi/min. In other words, for a Grade 300 super, 0.5 in. diameter strand, the minimum rate of testing should be 10,000 psi/min times 0.167 square in. (1.67 kips per min). The maximum rate of testing should be 100,000 psi/min times 0.167 square in. (16.7 kips per min).

The extensometer was placed on the strand before any testing began. The digital MTS output allowed for the data to be recorded automatically and manually without a pause in the data collection or tensioning. Once the output indicated a one per cent extension from the ten per cent initial load point, the rubber bands from the extensometer were cut, and the extensometer was removed and secured. The SATEC machine continued to tension the strand until failure. Data was saved, tension in the strand was released in the event the strand did not have a clear break, and the strand was removed from the hydraulic grips. An example of a completed test with a clear break is shown in Figure 3.10. From the output, stress-strain curves, load-displacement curves, modulus of elasticity, and elongation calculations were made.

Figure 3.10: Fractured Strand in SATEC Machine

3.2: Steel Relaxation Tests

There were three goals of the relaxation tests: to find out if the Grade 300 strand met the ASTM requirement of 2.5 and 3.5 per cent loss when stressed to 70 and 80 per cent breaking strength, respectively; to compare the results of the relaxation tests to the AASHTO LRFD Bridge Design Specification (2004 and 2005 Interim); and to find out if the tested length of the strand played any role in the outcome of the relaxation results. In order to conduct the testing, ASTM A416 (2005) and E328 (2002) were the primary guidelines used to conduct all of the testing. While ASTM A416 (2005) discusses properties of low-relaxation strand when stressed to 70 and 80 per cent of the strand's breaking strength, the focus of this testing was geared toward stressing at 70 per cent due to some issues encountered while stressing the strand. Figure 3.11 illustrates the setup for the relaxation tests conducted.

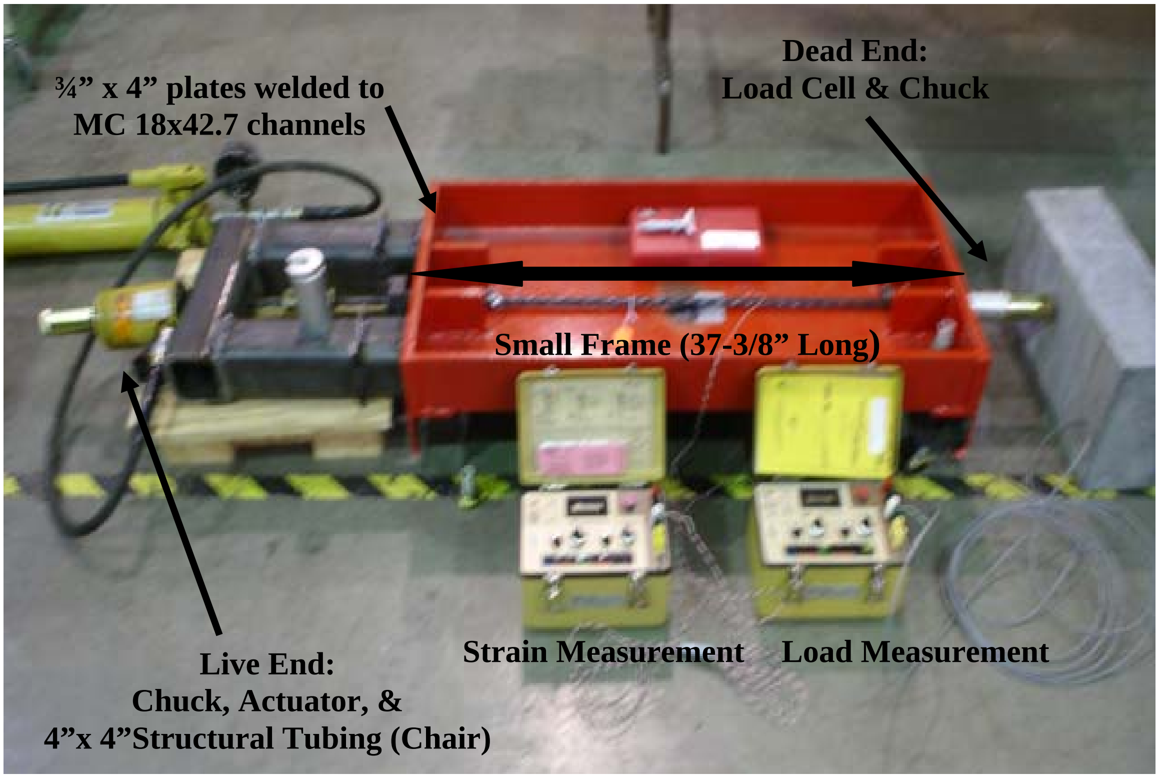

Figure 3.11: Schematic of Small Frame Test Setup

In order to ensure that the testing was done correctly, preliminary testing was conducted on Grade 270, 0.5 in. diameter, 0.153 square in. area strand. Excessive loss and negative results were due to the fact that standard chucks were being used to hold the force in the strand. During preliminary retesting using magnum chucks, the results provided confidence in the testing, since they complied with the expected relaxation properties listed in ASTM A416 (2005) of loss under 2.5 per cent.

Following the preliminary testing, testing was conducted on a number of other strands provided by Ronald Mann from Strand Tech Martin, Inc. While the primary objective was to test the material properties of the strand, the performance of three different lengths was also evaluated. The initial tests involved the small single frames, which were 37-3/8 in. long. The next set of tests used the medium sized frames (74-3/4 in. long), consisting of two small frames welded together. Finally, 200 hour tests were conducted on the large frames shown in Figure 3.12. The large frames (149.5 in. long) consisted of four of the small frames (two of the medium frames) welded together.

Figure 3.12: Large Frame

A summary of all relaxation testing meeting the ASTM minimum requirements is shown in Table 3.4.

Table 3.4: Relaxation Testing Summary

Type	Diameter	Area	Frame Size	Stress Level	Chucks
GR 270	0.5	0.153	Small	59.3%	Standard
GR 270	0.5	0.153	Small	62.0%	Magnum
GR 270	0.5	0.153	Small	60.6%	Magnum
GR 270	0.5	0.153	Medium	67.1%	Magnum
GR 270	0.5	0.153	Medium	68.7%	Magnum
GR 270	0.5	0.153	Large	75.0%	Magnum
GR 270	0.5	0.153	Large	75.1%	Magnum
GR 270	0.5	0.153	Large	75.4%	Magnum
GR 300	0.5	0.153	Small	59.9%	Magnum
GR 300	0.5	0.153	Small	58.6%	Magnum
GR 300	0.5	0.153	Small	56.8%	Magnum
GR 300	0.5	0.153	Medium	65.1%	Magnum
GR 300	0.5	0.153	Medium	67.1%	Magnum
GR 300	0.5	0.153	Large	81.1%	Magnum
GR 300	0.5	0.153	Large	74.5%	Magnum
GR 300	0.5	0.153	Large	73.8%	Magnum
GR 270	0.5	0.167	Medium	67.4%	Magnum
GR 270	0.5	0.167	Medium	67.3%	Magnum
GR 270	0.5	0.167	Medium	65.2%	Magnum
GR 300	0.5	0.167	Medium	64.8%	Magnum
GR 300	0.5	0.167	Medium	67.4%	Magnum
GR 300	0.5	0.167	Medium	68.9%	Magnum
GR 270	0.6	0.217	Medium	65.6%	Standard
GR 270	0.6	0.217	Medium	65.2%	Standard
GR 270	0.6	0.217	Medium	64.1%	Standard
GR 270	0.6	0.217	Large	69.9%	Standard

3.2.1: Relaxation Test Setup

The most difficult part of this testing was designing and building the test frames. ASTM E328 (2002) is not specific when it comes to the testing frame necessary to carry out the relaxation test. For this design, the maximum expected compressive force to act on the endplate and the frame was based on the use of a Grade 300, 0.6 in. diameter, 0.217 square in. area strand. Based on tensioning the strand to 80 per cent of ultimate, the compressive force on the frame would be 80 per cent times 300 ksi times 0.217 square in., or 52.1 kips. The design of the frame was based on the limit states of compression, while the design of the endplates was based on flexure. The first step was to design the relaxation bed frames.

3.2.1.1.: Design of the Frame Bed

The frame selected had to meet certain criteria. First, it had to be at least 60 strand diameters in length in accordance with ASTM A416 (2005). The small frames (37-3/8 in. long) were based on the requirement of the largest diameter strand for this testing (60 times 0.6 in. diameter strand, or 36 in.). Secondly, it had to have flanges wide enough to weld endplates on both ends to support the chair that was used to tension the strand. Finally, the frame had to have the compressive strength necessary to withstand the compression of the chucks and load cell on both the dead end of the frame and the chuck and spacers on the live end of the frame. Using materials on hand, the MC18x42.7 channel's compressive strength was evaluated.

According to AISC Steel Construction Manual, 13th Edition, Chapter E "Design of Members for Compression" (2005), the design compressive strength of a section is determined from the controlling limit states of flexural buckling, torsional buckling and flexural-torsional buckling. Since the flange and web of the frame were compact in accordance with Table B4.1 of the AISC Steel Construction Manual (2005), Section E3 "Compressive Strength for Flexural Buckling of Members without Slender Elements" and Section E4 “Compressive Strength for Torsional and Flexural-Torsional Buckling of Members without Slender Elements” were used to find the controlling elastic critical buckling stress of the channel. Since the MC channel was singly symmetrical, the elastic critical buckling stress was determined by the limit states of flexural buckling and flexural-torsional buckling, as shown in Equations 3.1 and 3.2, respectively. To ensure a conservative design, the yield stress of the frame, which was unknown, was assumed to be 36 ksi, and the long frame length of 149.5 in. was used for all calculations.

$$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2} \quad \textbf{(3.1)}$$

$$F_{eyz} = \left(\frac{F_{ey} + F_{ez}}{2H}\right)\left(1 - \sqrt{1 - \left(\frac{4F_{ey}F_{ez}H}{\left(F_{ey} + F_{ez}\right)^2}\right)}\right) \quad \textbf{(3.2)}$$

where:

F_e = elastic critical buckling stress (ksi)

E = modulus of elasticity (ksi)

K = effective length factor (taken as 1.0)

L = length of member (in.)

r = governing radius of gyration (in.)

F_{eyz} = elastic flexural-torsional buckling stress (ksi)

H = flexural constant

F_{ey} = elastic flexural buckling stress about minor axis (ksi)

F_{ez} = elastic torsional buckling stress

Evaluating Equations 3.1 and 3.2, the elastic flexural buckling stress and elastic flexural-torsional buckling stress of the frame were 14.8 ksi and 40.5 ksi, respectively. With the flexural elastic critical buckling stress of 14.8 ksi less than 0.44 times the frame yield stress (0.44 times 36 ksi, or 15.84 ksi), the flexural buckling stress of the frame was determined by Equation 3.3 to be 13 ksi.

$$F_{cr} = 0.877 F_e \quad \textbf{(3.3)}$$

where:

F_e = controlling elastic critical buckling stress (ksi)

F_{cr} = flexural buckling stress (ksi)

Using Equation 3.4, the nominal design compressive strength of the frame was determined to be 147 kips. The frame selected was suitable for the testing to be conducted since the nominal design compressive strength was greater than the required factored compressive load (1.6 live load factor x 52.1 kips, or 83.4 kips).

$$\phi P_n = F_{cr} A_g \quad \textbf{(3.4)}$$

where:

ϕP_n = factored nominal axial strength (kips)

F_{cr} = flexural buckling stress (ksi)

A_g = gross area of frame (in.^{2})

3.2.1.2.: Design of the Frame Endplates

The endplates for the frame were selected once the design for the frame bed was designed. The keys to the endplate design were ensuring that the plates did not yield under load and ensuring that the plates would fit on the ends of the channel. The plates would be subjected to the same maximum, factored axial load of 83.4 kips. Using Equation 3.5, the minimum cross-sectional area required for the plate to avoid yielding under load was 2.3 square in.

$$A_{req'd} = \frac{\phi P_n}{F_y} \qquad \textbf{(3.5)}$$

where:

ϕP_n = factored nominal axial strength (kips)

F_y = yield stress of the plate (ksi)

$A_{req'd}$ = required area of the plate (in^2)

With the 3.95 in. flange width of the MC18x42.7 channel, the required widths of the plates were approximately 4 in. In order to meet the required area from Equation 3.5, this meant that the required thickness of the plates was 0.58 in. As a result, the endplates selected were A36, ¾ in. by 4 in. plates, with a factored nominal axial strength of approximately 97 kips (0.9 times 36 ksi times ¾ in. times 4 in., or 97.2 kips). To further enhance the strength and stability of the plates, two A36, ¾ in. by 4 in. by 4 in. plates were welded to the backside of the endplates and the web of the MC 18 x 42.7 channel. Figure 3.13 provides a closer view of the MC18x42.7 channel, endplates, and stability plates.

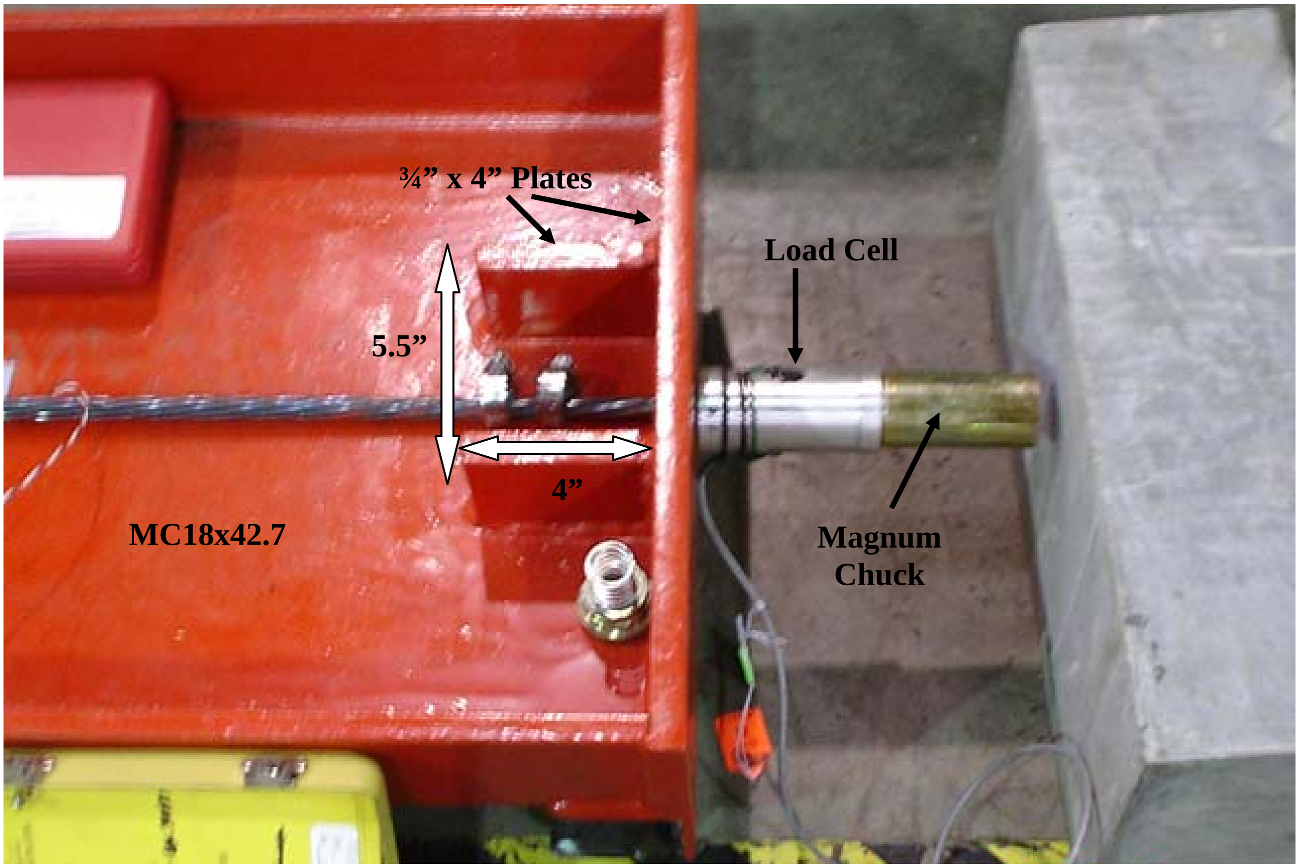

Figure 3.13: MC18x42.7 with ¾ in. by 4 in. Plate

3.2.1.3.: Fabricated Chair and Selection of Chucks

The fabricated chair was made of HSS4x4 structural tubing with a 0.75 in. hole cut out. The hole is big enough for the largest diameter strand, 0.6 in., to fit through without rubbing on the sides, which could have resulted in friction. The chair was used on the live end, with the purpose of being the foundation for the actuator to tension the strand and allowing the chucks to set.

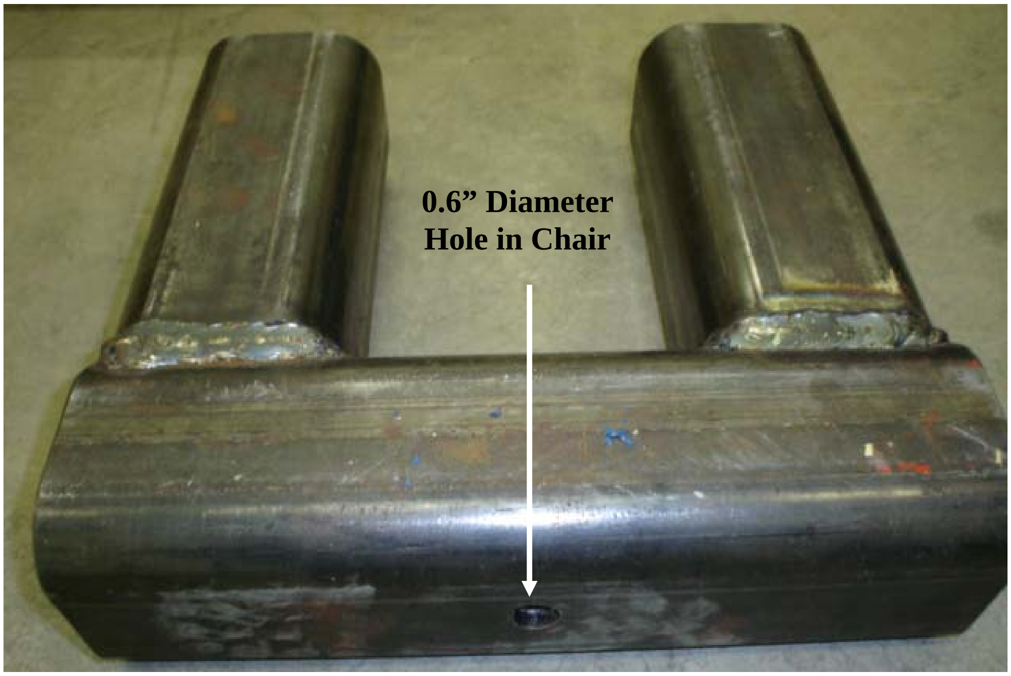

Figure 3.14: Chair made from Structural Tubing

The two types of chucks used in testing were standard chucks, silver in color, and magnum chucks, gold in color. The German manufactured chucks used in the testing were purchased from Prestress Supply in Lakeland, Florida (1-800-328-8036 or www.pci.org). The silver, regular chucks have been out on the market for quite some time. The magnum chucks were developed for use with the Grade 300 strand, although they can actually be used on both the Grade 270 and Grade 300 strand. Only available during the time of testing for 0.5 in. diameter strand, the magnum chuck had a longer body, heavier spring, thicker teeth and jaws with more teeth than the regular chuck. These characteristics proved to be valuable in relaxation testing. The meatier teeth reduced the losses attributed to seating during the first couple of minutes of testing, allowing all of the strands tested to provide satisfactory results as explained in greater detail in Chapter 4. A side-by-side comparison of the magnum chuck and the standard chuck bodies, gripping jaws with teeth, and springs are displayed in Figure 3.15.

Figure 3.15: Comparison of Standard and Magnum Chucks

3.2.2: Relaxation Test Instrumentation

Perhaps the most important aspect behind conducting relaxation tests is ensuring that the test is conducted in an environment where temperature remains constant. ASTM A416 (2005) requires that the relaxation test is conducted at 68 $\pm$ 3.5 F. Relaxation losses tend to increase as the temperature increases. ASTM E328, Standard Test Methods for Stress Relaxation for Materials and Structures (2002), reiterates the importance of temperature by stating that it is the single most important factor in the test. The ASTM recommends a temperature-controlled room capable of maintaining constant temperature with an automatic device. The Creep and Shrinkage Room in the Virginia Tech Structures and Materials Laboratory was used as the test space environment. The temperature in the room ranged between 22.0 C (69.8 F) and 22.5 C (72.5 F) throughout the testing, although for the large majority of the tests, the temperature remained steady at 22.1 C (71.78 F).

Another key to the relaxation test is to maintain the stressed strand at a constant strain. In order to measure the strain during testing, a Vishay strain gage was applied to the center of the frame in accordance with the Vishay Measurements Group Instruction Bulletin B-137-16 (1979). Strain was constantly measured and recorded periodically using a strain gauge indicator. The output from the strain gauge indicator never changed by more than $\pm$ 2 microstrain during any of the tests. The maximum change of strain was 60 microstrain to 58 microstrain, exhibiting a change in strain within the ASTM E328 (2002) limit of $\pm 2.5 \times 10^{-5}$ mm/mm.

The final piece of key instrumentation involved the measurement of tension in the strand. The load cells had to be able to measure and withstand a maximum load of 52.1 kips (80 per cent the breaking strength of a Grade 300, 0.6 in. diameter, 0.217 square in. strand). The load cells were made from 6061 Aluminum, with a cross-sectional area of 2.7 square in. The tested strand fit in the 0.75 in. diameter hole of the load cell shown in Figure 3.16. The cross-sectional area of the load cell was determined by taking the outside area (3.14 square in.) minus the inside area (0.44 square in.). Dividing the maximum load needed for the testing (52.08 kips) by the load resistance factor for compression of 0.9 (AISC Steel Construction Manual 2005) and the 2.7 square in. cross-sectional area, the maximum stress applied to the load cell would be 21.4 ksi. According to Table 7.4.2.1-1 of Chapter 7, AASHTO LRFD (2004), the compressive yield stress for

6061 Aluminum is 35 ksi. In other words, the full-bridge load cells shown in Figure 3.16 met the required compressive strength necessary to conduct the relaxation tests.

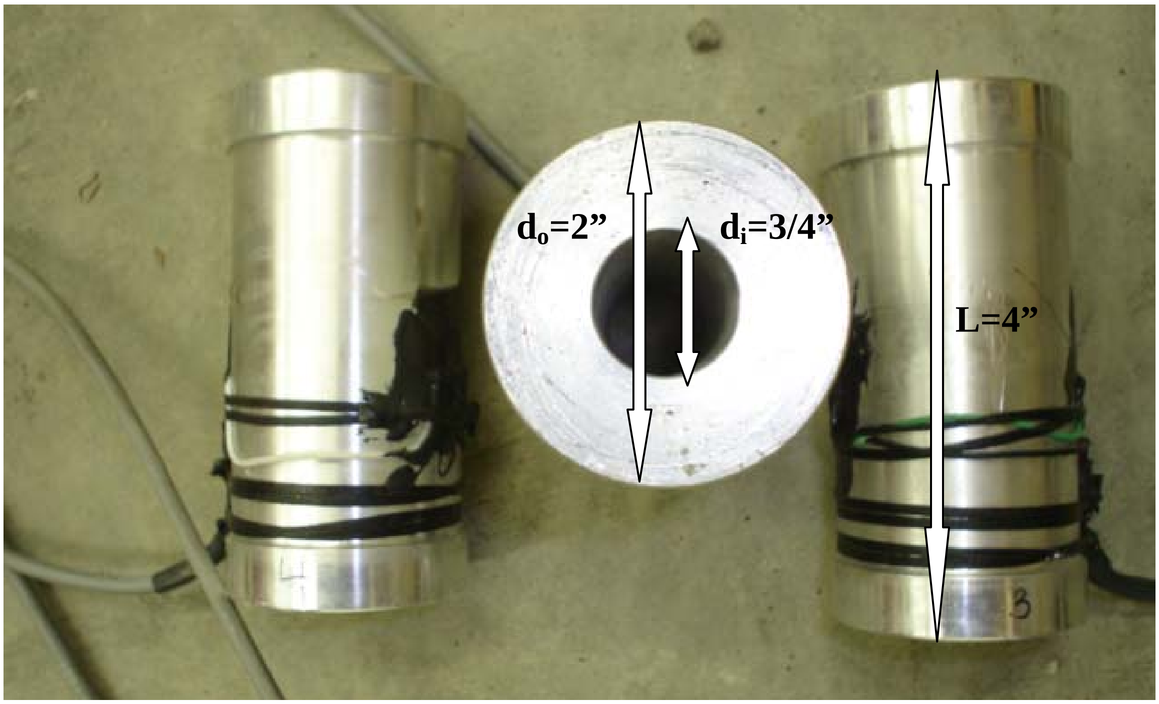

Figure 3.16: 6061 Aluminum Load Cells

After making the full-bridge load cells, they were calibrated to 45 kips using the universal SATEC MK-III machine at the Virginia Tech Structures and Materials Laboratory. Each of the 11 load cells was connected to a strain gauge indicator and the SATEC machine shown in Figure 3.17.

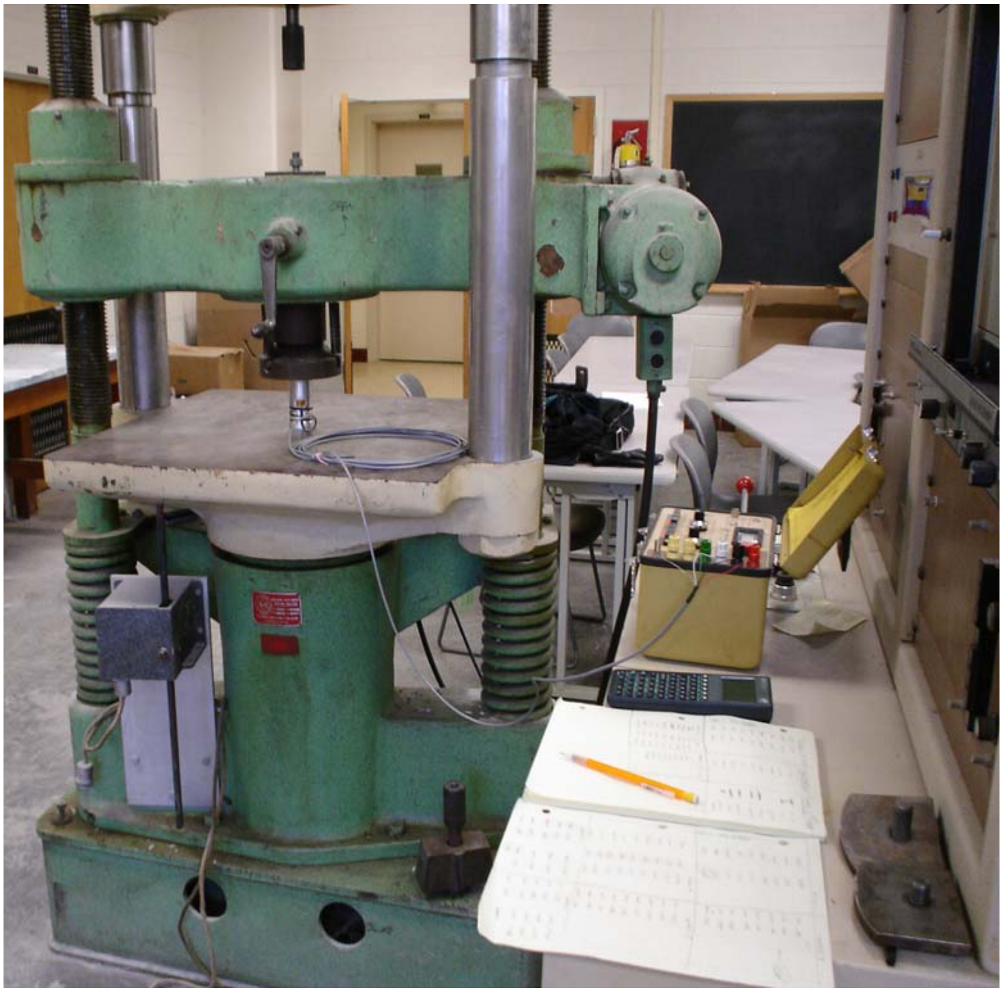

Figure 3.17: Load Cell Calibration

Loads were measured and compared every 5,000 pounds. An example of the plots made for each calibration demonstrating the precision between the SATEC MK-III and the strain gauge reading output is shown in Figure 3.18.

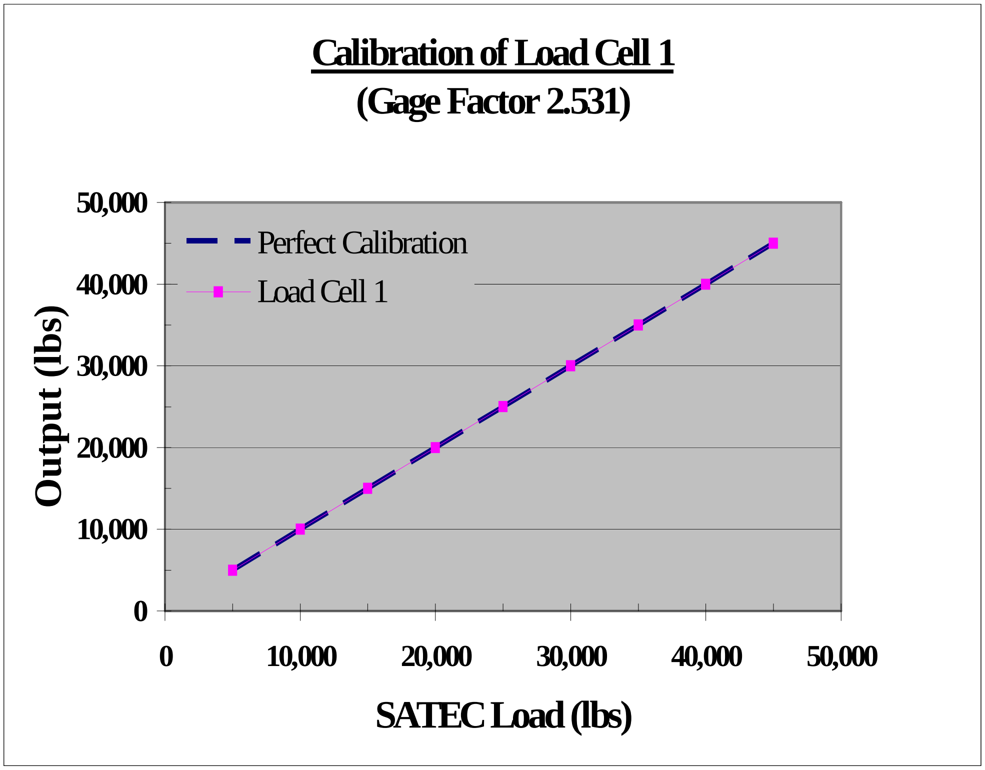

Figure 3.18: Sample Calibration of Load Cell

3.2.3: Relaxation Test Procedures

All of the equipment was placed in the temperature controlled room 24 hours prior to the beginning of any testing. It is recommended in ASTM E328 Section 10 (2002) that testing materials with strain gages or extensometers be exposed in the appropriate test temperature climate for an appropriate amount of time to obtain dimensional stability prior to testing. The temperature was measured continuously and was recorded periodically in accordance with E328 Section 7.2 (2002). Original testing in the small frames involved 0.5 in. diameter strand that was 37-3/8 in. long. This met the ASTM A416 (2005) requirement that the test length be a minimum of 60 times the nominal diameter (60 times 0.5 in. diameter or 30 in. minimum test length which is less than the 37-3/8 in. actual test length). As the strand was placed in the frame, a small aluminum angle was clamped onto the strand at each end as demonstrated in Figure 3.19.

Figure 3.19: Aluminum Angle for Depth Micrometer

A very small amount of tensile force was put onto the strand using the actuator seen in Figure 3.20. As the pressure in the actuator was held, the clamps holding the angles to the strand were tightened to ensure that they were facing upright. The fabricated angles had small holes cut in them, so that a depth micrometer could fit through it. Once the angles were tightened to the strand, the actuator tensioned the strand to 80 per cent of its breaking strength. As the force in the actuator was held, the rest of the frame components were tightened. Then, the force in the actuator was released. When tensioning the strands in the small and medium frames, the load typically dropped to approximately 50 per cent of the strand's breaking strength. This was due to the seating losses and chuck slip. In the large frames, the load typically stayed above 70 per cent of the strand's ultimate breaking strength, so no retensioning was necessary. In every test where the load dropped below the 70 per cent standard, the process was repeated, with the actuator retensioning the strand to 80 per cent of its breaking strength. Every iteration resulted in the frame system capturing more tension force. Tensioning the strand occurred over a period of between 3 and 5 minutes in accordance with ASTM A416, 6.5.4 (2005). Initial readings were taken 1 minute after total load application. The initial load was approximately 60 to 65 per cent of the breaking stress in small frames, 63 to 68 per cent in medium frames, and 70 to 80 per cent in large frames.

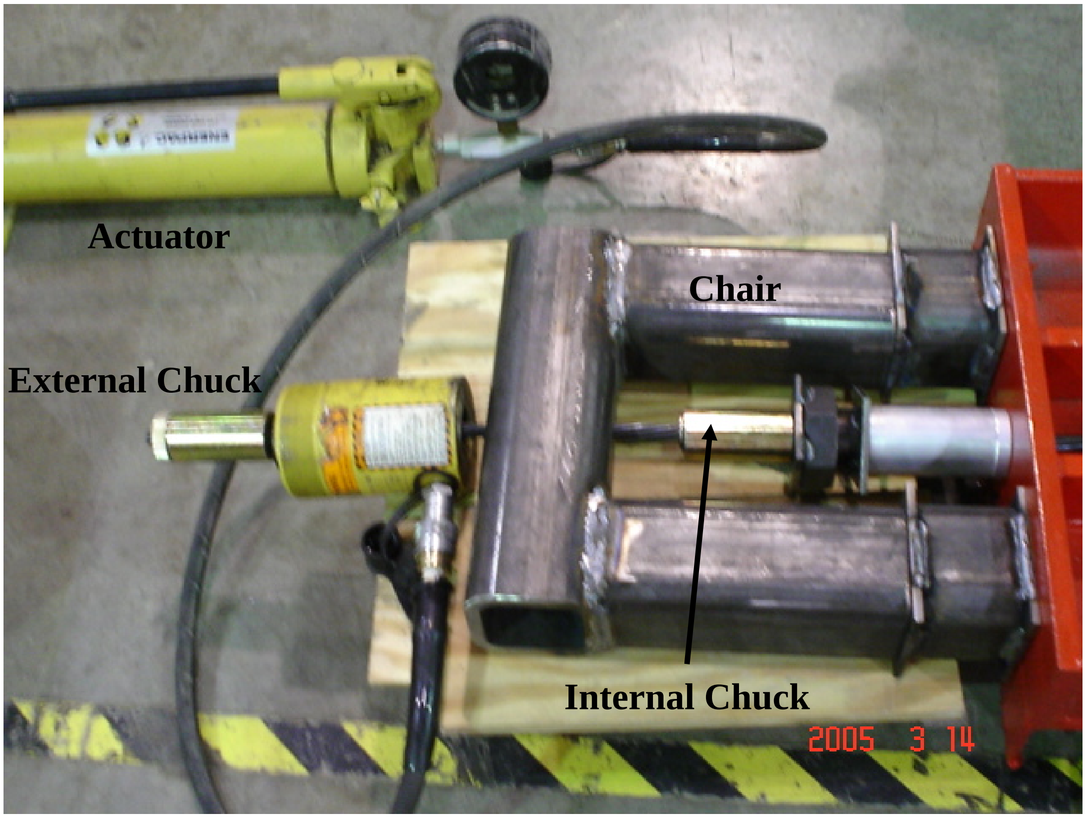

Figure 3.20: Actuator and Tensioning Equipment

Once the testing actually started, data was recorded periodically. With relaxation occurring exponentially, the first several hours were critical for data collection. Data recorded included time, temperature, chuck slip, strain, and load. All time data was collected from the same clock. All temperature data was collected from the automated thermometers in the Creep and Shrinkage Room. Chuck slip was measured as shown in Figure 3.21 using the depth micrometer on both the dead end (chuck and load cell end) and the live end (tensioning end). This was the most difficult part of the data collection. A digital depth micrometer would probably be a better choice for future tests.

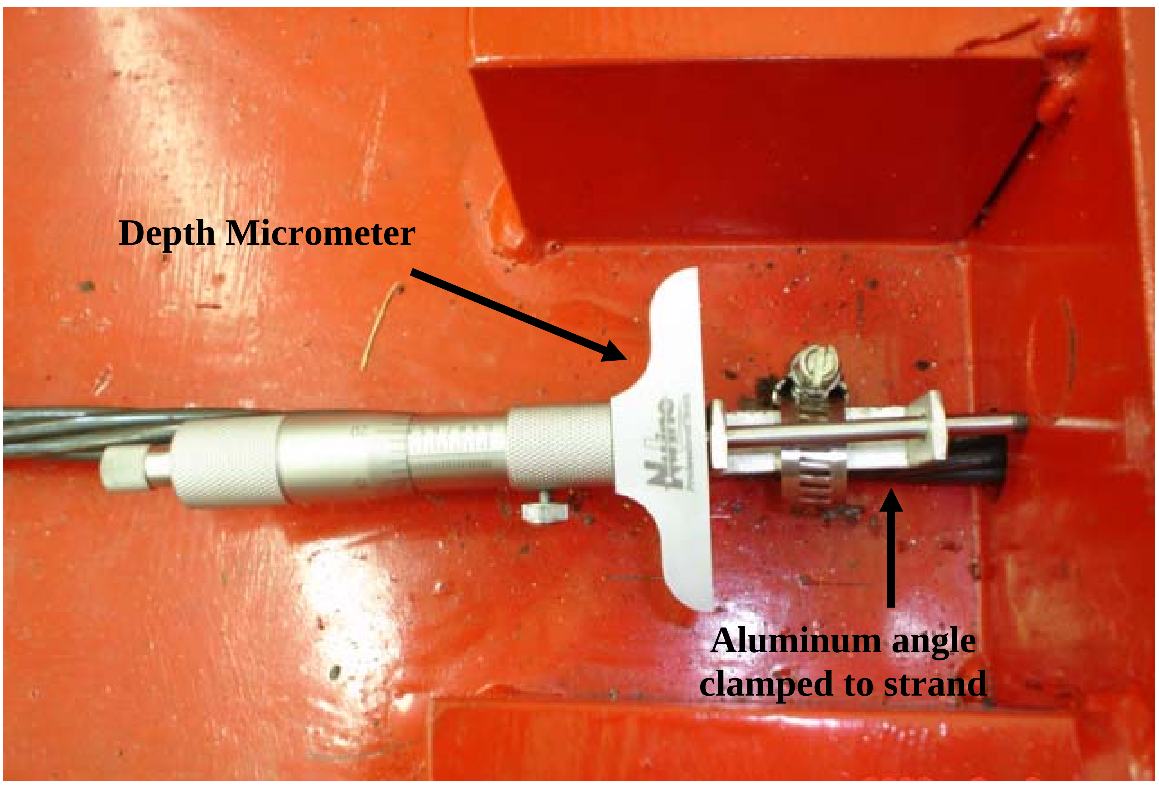

Figure 3.21: Depth Micrometer Measurements

Strain and load information were collected using strain gauge indicators. The use of two switch and balance units allowed ten frames to be tested at the same time. One switch and balance unit and strain gauge indicator collected ten load readings, and the other collected ten strain readings. For all of the tests, data was collected every minute for the first 10 minutes. The collection of data was less frequent over time, generally once or twice a day, as the change in relaxation losses diminished. After the first 10 minutes of data collection, the external chuck, actuator, and chair were removed from the test frame. The springs for the chucks on each end were put in place for safety.

CHAPTER IV
RESULTS AND DISCUSSION

4.1: Tension Tests

4.1.1: Introduction to Tension Tests

A total of 30 tension tests were conducted in order to determine the ultimate strength, yield strength, modulus of elasticity and elongation properties of various samples of strand. The tension tests were completed by following the procedures presented in Chapter 3. This section presents the results and details of these 30 tests. Tables 4.1, 4.2, and 4.3 provide the mechanical properties measured during tension tests.

Table 4.1: Tension Results of Grade 270 and 300, 0.5 in. Diameter, Regular Strands

Results of Grade 270 and Grade 300, 0.5 in. Diameter, Regular Strands								
Grade	Diameter (in.)	Area (in.^{2})	Yield (ksi)	Ultimate (ksi)	E (ksi)	Elongation (%)	Grips	Break
270	0.5	0.153	249	268	27300	4.6%	AF	G
270	0.5	0.153	258	275	29700	7.2%	AF	G
270	0.5	0.153	255	274	29400	7.4%	AF	G
270	0.5	0.153	257	276	28400	7.8%	AF	G
270	0.5	0.153	273	326	27700	8.3%	SG	CM
270	0.5	0.153	265	314	28000	8.6%	SG	CM
300	0.5	0.153	277	304	27100	5.6%	AF	G
300	0.5	0.153	278	305	28000	6.3%	AF	G
300	0.5	0.153	277	306	28300	8.6%	AF	G
300	0.5	0.153	284	305	29500	7.2%	AF	G
300	0.5	0.153	270	348	28300	9.4%	SG	CM
300	0.5	0.153	298	354	30200	8.5%	SG	CM

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.
G: Break of less than all seven strands in the grips.
CM: Clear break of all seven strands in the middle of the specimen.
CG: Clear break of all seven strands near the grips.

Table 4.2: Tension Results of Grade 270 and 300, 0.5 in. Diameter, Super Strands

Results of Grade 270 and Grade 300, 0.5 in. Diameter, Super Strands								
Grade	Diameter (in.)	Area (in.^{2})	Yield (ksi)	Ultimate (ksi)	E (ksi)	Elongation (%)	Grips	Break
270	0.5	0.167	248	308	29100	7.7%	SG	CM
270	0.5	0.167	277	308	29000	6.8%	SG	CM
270	0.5	0.167	252	302	28900	7.4%	SG	G
270	0.5	0.167	269	308	29600	7.4%	SG	CG
270	0.5	0.167	272	294	30000	6.2%	SG	G
300	0.5	0.167	287	336	28700	7.2%	SG	G
300	0.5	0.167	285	338	29000	7.9%	SG	CM
300	0.5	0.167	295	338	30300	7.4%	SG	CG
300	0.5	0.167	278	343	28100	7.2%	SG	G
300	0.5	0.167	294	339	30400	7.9%	SG	CM
300	0.5	0.167	272	328	29079	7.3%	SG	CM

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.
G: Break of less than all seven strands in the grips.
CM: Clear break of all seven strands in the middle of the specimen.
CG: Clear break of all seven strands near the grips.

Table 4.3: Tension Results of Grade 270, 0.6 in. Diameter, Regular Strands

Results of Grade 270, 0.6 in. Diameter, Regular Strands								
Grade	Diameter (in.)	Area (in.^{2})	Yield (ksi)	Ultimate (ksi)	E (ksi)	Elongation (%)	Grips	Break
270	0.6	0.217	260	277	29900	7.6%	AF	G
270	0.6	0.217	261	273	28700	5.7%	AF	G
270	0.6	0.217	280	316	28500	6.5%	SG	G
270	0.6	0.217	283	316	29700	6.8%	SG	G
270	0.6	0.217	283	314	28600	6.1%	SG	G
270	0.6	0.217	284	314	28400	7.1%	SG	G
270	0.6	0.217	265	315	28100	7.5%	SG	CG

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.
G: Break of less than all seven strands in the grips.
CM: Clear break of all seven strands in the middle of the specimen.
CG: Clear break of all seven strands near the grips.

4.1.2: Ultimate Stress

The ultimate stress was determined by tensioning the strand until there was a break in one or more of the wires. In most prestressing applications, the strand is tensioned between 70 and 80 per cent of the ultimate breaking strength. As a result, it is imperative that the strand is able to meet the minimum required ultimate strength.

4.1.2.1: Ultimate Stress Results

The first strands tested involved the industry standard Grade 270, 0.5 in. diameter, 0.153 square in. area strand. Four tests were performed using aluminum foil as a grip cushioning material, while two tests used special grips. Every strand sample tested met the ASTM minimum ultimate stress of 270 ksi (breaking strength of 270 ksi times 0.153 square in., or 41.31 kips), as demonstrated in Figure 4.1.

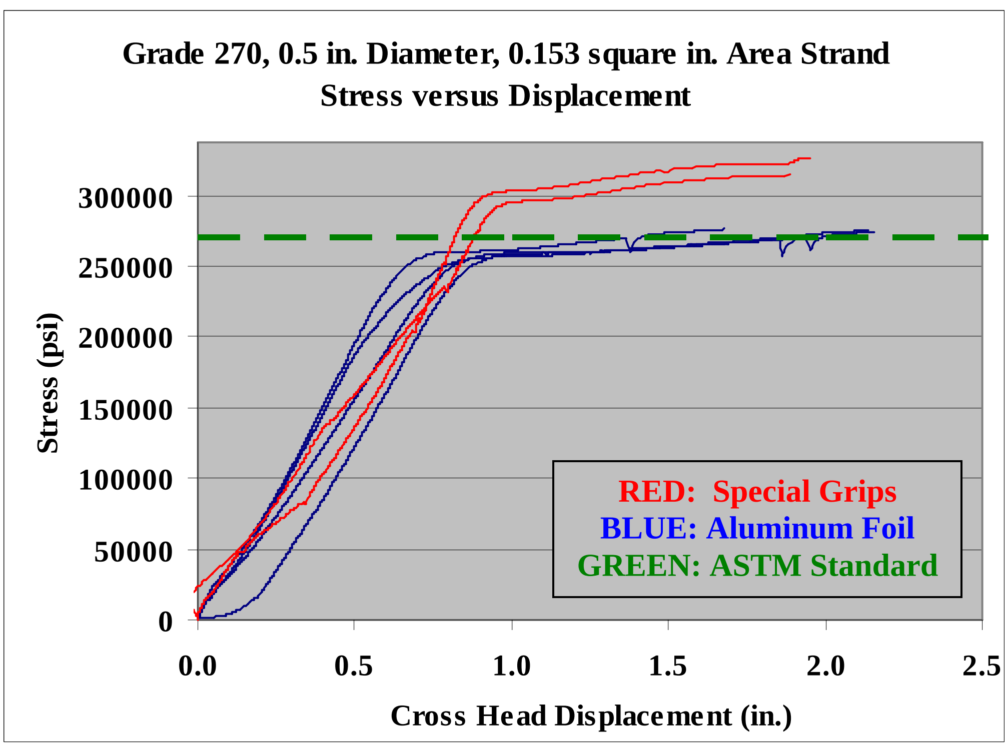

Figure 4.1: Grade 270, 0.5 in. Diameter, Regular, Stress versus Displacement

With positive results from the Grade 270, 0.5 in. diameter, 0.153 square in. area strands, the next strands tested were the Grade 300, 0.5 in. diameter, 0.153 square in. area strands. The six strands tested included four using aluminum foil as cushioning material and two using the aluminum inserts and aluminum oxide. All six of the strands tested met the ASTM minimum ultimate stress of 300 ksi (breaking strength of 300 ksi times 0.153 square in., or 45.9 kips). Figure 4.2 provides the stress versus hydraulic head displacement curves for the Grade 300, 0.5 in. diameter, 0.153 square in. area strands.

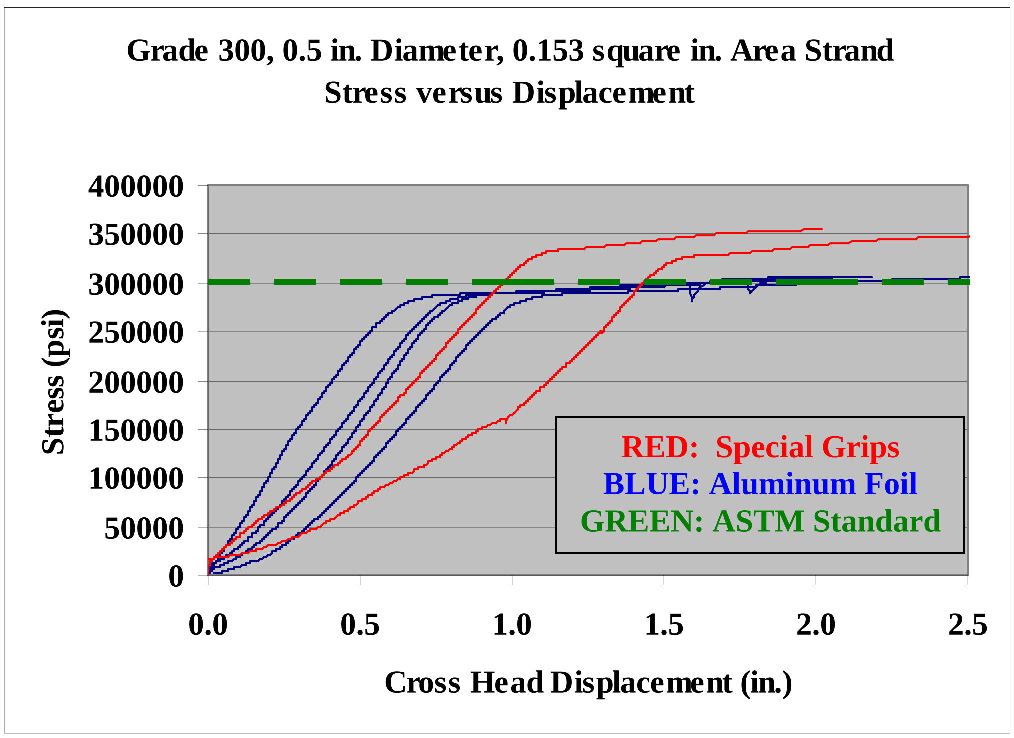

Figure 4.2: Grade 300, 0.5 in. Diameter, Regular, Stress versus Displacement

The next strands tested were the super strands. The super strands have a cross-sectional area larger than the regular strands of the same diameter. Several attempts were made to test both the Grade 270 and Grade 300 super strands using aluminum foil as cushioning material for the V-grips; however, not a single strand met the ASTM criteria. Every strand failed prematurely near the expected yield strength of the strand due to excessive lateral pressure from the V-grips.

Subsequent tests were performed using the special grips with the aluminum foil, aluminum oxide, and epoxy as described in Chapter 3. The Grade 270, 0.5 in. diameter, 0.167 square in. area strands were tested first using these special grips. The five strands tested with the special grips met the ASTM minimum ultimate stress of 270 ksi (breaking strength of 270 ksi times 0.167 square in., or 45.1 kips). Plots for the stress versus hydraulic head displacement for the Grade 270, 0.5 in. diameter, 0.167 square in. area strand are shown in Figure 4.3.

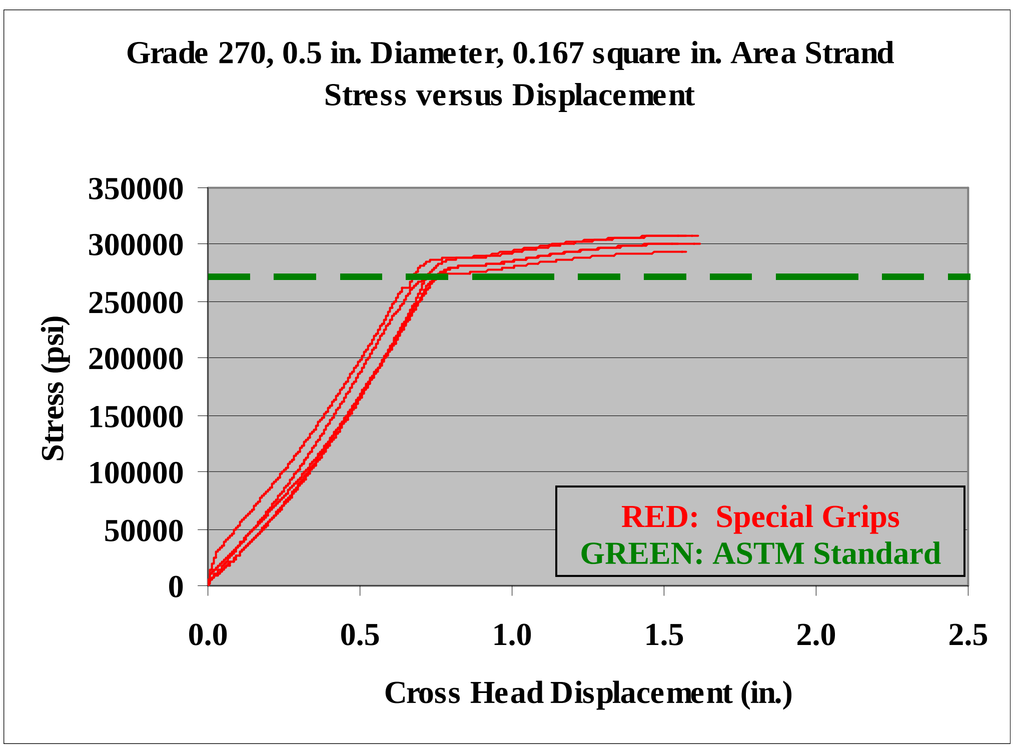

Figure 4.3: Grade 270, 0.5 in. Diameter, Super, Stress versus Displacement

The other super strands tested were the Grade 300, 0.5 in. diameter, 0.167 square in. area strand. With multiple tests using aluminum foil and V-grips failing prematurely, six other strands were tested with the special grips. All of the Grade 300 super strands with special grips met the ASTM minimum ultimate stress of 300 ksi (breaking strength of 300 ksi times 0.167 square in., or 50.1 kips). The stress versus hydraulic head displacement for the Grade 300, 0.5 in. diameter, 0.167 square in. area strand is shown in Figure 4.4.

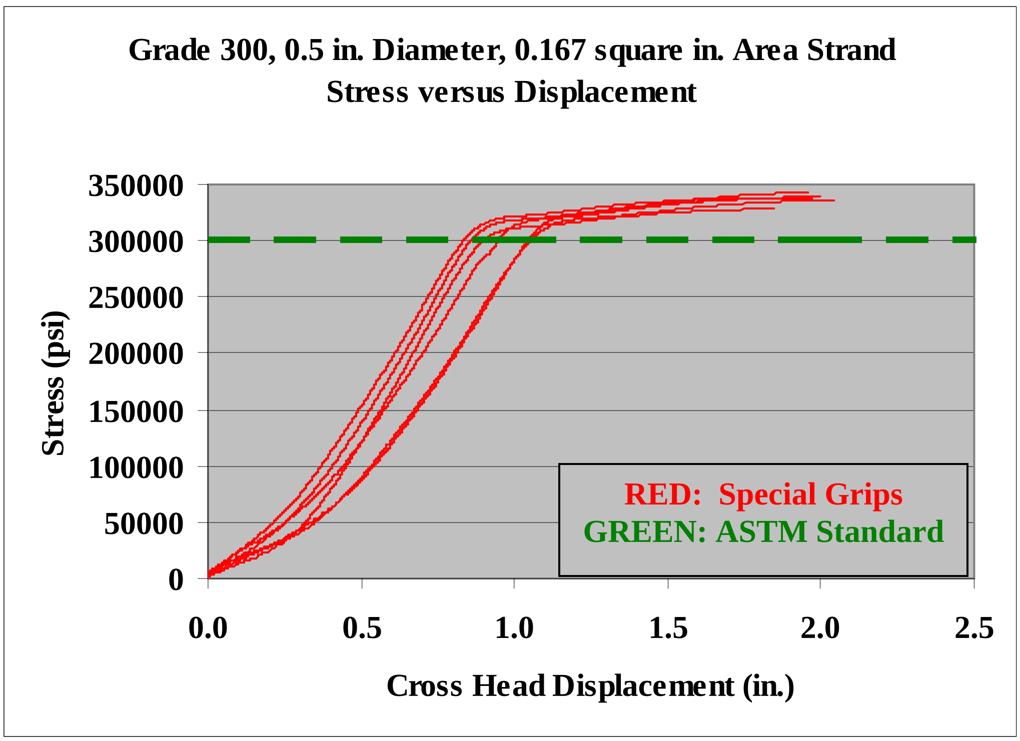

Figure 4.4: Grade 300, 0.5 in. Diameter, Super, Stress versus Displacement

The final strand tested was the Grade 270, 0.6 in. diameter, 0.217 square in. area strand. Two strands were tested with aluminum foil, and another five were tested with the special grips. While two tests with aluminum foil met the ASTM standard, three other strands not presented in this research failed prematurely at a stress less than 270 ksi. The seven results presented in Figure 4.5 all met the ASTM minimum ultimate stress of 270 ksi (breaking strength of 270 ksi x 0.217 square in. or 58.6 kips). The Grade 300 strand equivalent was unavailable during testing, so no comparison was made between the Grade 300 and Grade 270, 0.6 in. diameter strands.

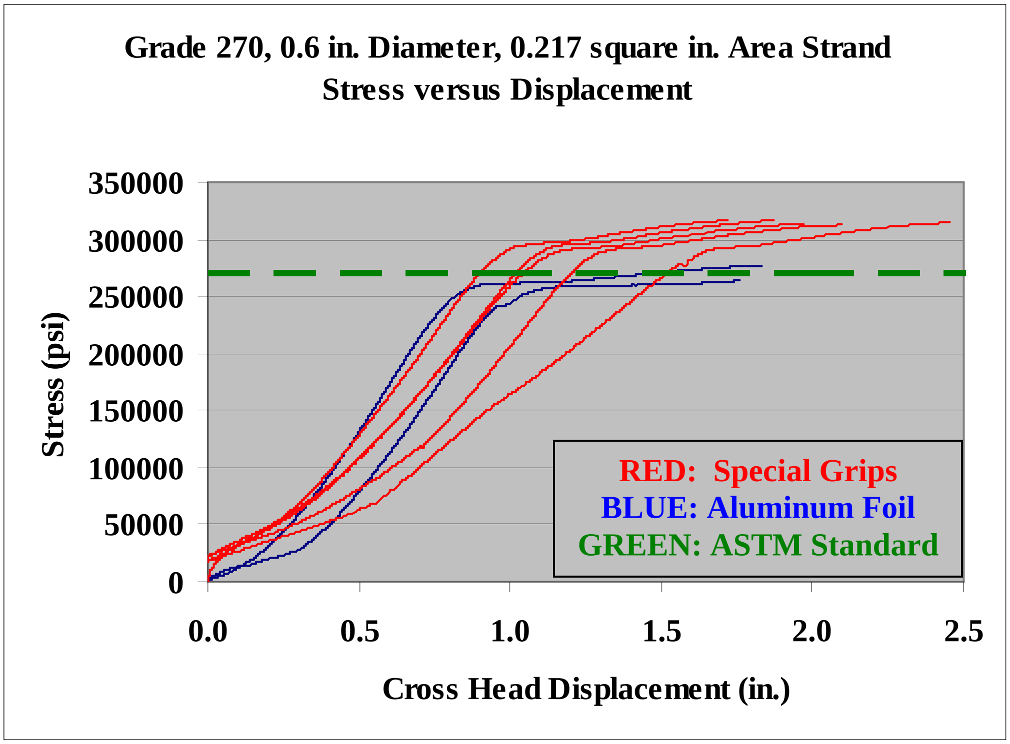

Figure 4.5: Grade 270, 0.6 in. Diameter, Regular, Stress versus Displacement

4.1.2.2: Ultimate Stress Analysis

Every strand tested was manufactured to the meet the minimum guaranteed ultimate minimum breaking stress outlined in ASTM A416 (2005). Some of the tests resulted in failure just above the minimum required breaking stress. However, in other tests, the strands easily surpassed the minimum requirement by more than 30 ksi. As demonstrated in the analysis and tables that follow, the significant factor for when and how the strands failed was the way the strand was gripped in the SATEC testing machine.

The first strands analyzed and compared were the Grade 270 and Grade 300, 0.5 in. diameter, 0.153 square in. area strands. Their ultimate breaking stress comparisons are shown in Table 4.4.

Table 4.4: Breaking Stress Analysis of 0.5 in. Diameter, Regular Strand

Grade	Diameter (in.)	Area (in.^{2})	Minimum Ultimate Breaking Stress Req'd (ksi)	Ultimate Breaking Stress Tested (ksi)	Ratio: fpu Tested / fpu Req'd	Type of Grips	Type of Break
270	0.5	0.153	270	268	0.99	AF	G
270	0.5	0.153	270	275	1.02	AF	G
270	0.5	0.153	270	274	1.01	AF	G
270	0.5	0.153	270	276	1.02	AF	G
270	0.5	0.153	270	326	1.21	SG	CM
270	0.5	0.153	270	314	1.16	SG	CM
Grade 270 Averages			270	289	1.07	-------	-------
300	0.5	0.153	300	304	1.01	AF	G
300	0.5	0.153	300	305	1.02	AF	G
300	0.5	0.153	300	306	1.02	AF	G
300	0.5	0.153	300	305	1.02	AF	G
300	0.5	0.153	300	348	1.16	SG	CM
300	0.5	0.153	300	354	1.18	SG	CM
Grade 300 Averages			300	320	1.07	-------	-------

Key

AF: Aluminum foil and V-grips used to grip the strand.

SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.

G: Break of less than all seven strands in the grips.

CM: Clear break of all seven strands in the middle of the specimen.

CG: Clear break of all seven strands near the grips.

For the Grade 270, 0.5 in. diameter, regular area strand, the strand surpassed the minimum required breaking stress on average by 6.8 per cent. Strand tested using aluminum foil and V-grips averaged a breaking stress of 273 ksi (41.8 kips); meanwhile, strand tested using the aluminum inserts, aluminum oxide and V-grips averaged a breaking strength of 320 ksi (49 kips). All three failures with the aluminum foil involved the fracture of a single strand. For the tests conducted using aluminum foil, the actual breaking strength exceeded the required breaking strength by an average of 1 per cent. Meanwhile, the special grips allowed the strands to reach their true full breaking strength; in doing so, the results of the tests were clear breaks in the middle of the test specimens. All seven wires broke simultaneously, and the strand surpassed its breaking stress by an average of 18.5 per cent.

When comparing the results obtained in this testing to the tensile tests from Shenoy and Frantz (1991) displayed in Table 2.2, it is evident that both the aluminum foil and special grip methods used in this testing provide more reliable results when compared to their testing methods. Shenoy and Frantz (1991) used six different methods to test six each Grade 270, 0.5 in. diameter, 0.153 square in. area strands. When tensioning the strand with V-grips, chucks, or a combination of both, the average breaking stress of the strand was 237 ksi. The premature strand failure occurred in the jaws of the chucks, and the strand breaking stress was only 88 per cent of the minimum required breaking stress of 270 ksi. With their preferred method of using the V-grips, chucks, and sleeves (12 in., 14 in., and 20 in. long sleeves in the three tests), the average breaking stress of the three Grade 270 strands was 268 ksi, still 2 per cent shy of the minimum required breaking stress. Their preferred method averaged 21 ksi below the average breaking stress obtained through this research using the aluminum foil grip method and aluminum oxide with aluminum tubing method.

The Grade 270 results and analysis generally coincided with the pattern displayed by the 0.5 in. diameter, 0.153 square in. area, Grade 300 strand. The strands' average tested breaking strength was 7 per cent higher than the minimum required breaking strength. While the aluminum foil cushioning technique was found to be suitable for the purposes of guaranteeing the minimum breaking stress, the aluminum insert and aluminum oxide method provided better results once again. The average breaking stress for the tensioned strand using aluminum foil as the cushioning material was 305 ksi (46.7 kips), with each strand failing with a single wire fracturing at one of the grips. This constitutes an ultimate breaking stress 1.75 per cent higher than the minimum required. Meanwhile, the special grips on the Grade 300, 0.5 in. diameter strand allowed the strand to have clear breaks in the middle of the strand and surpass the minimum required breaking stress by 17 per cent on average. This coincides with an average breaking stress of 351 ksi (53.7 kips).

The next strands analyzed were the Grade 270 and Grade 300, 0.5 in. diameter, 0.167 square in. area strands shown in Table 4.5. Numerical comparisons were not made between super strands gripped with aluminum foil versus the special grips, since all of the strands gripped with aluminum foil broke prematurely.

Table 4.5: Breaking Stress Analysis of 0.5 in. Diameter, Super Strand

Grade	Diameter (in.)	Area (in.^{2})	Minimum Ultimate Breaking Stress Req'd (ksi)	Ultimate Breaking Stress Tested (ksi)	Ratio: fpu Tested / fpu Req'd	Type of Grips	Type of Break
270	0.5	0.167	270	308	1.14	SG	CM
270	0.5	0.167	270	308	1.14	SG	CM
270	0.5	0.167	270	302	1.12	SG	G
270	0.5	0.167	270	308	1.14	SG	CG
270	0.5	0.167	270	294	1.09	SG	G
Grade 270 Averages			270	304	1.13	-------	-------
300	0.5	0.167	300	336	1.12	SG	G
300	0.5	0.167	300	338	1.13	SG	CM
300	0.5	0.167	300	338	1.13	SG	CG
300	0.5	0.167	300	343	1.14	SG	G
300	0.5	0.167	300	339	1.13	SG	CM
300	0.5	0.167	300	328	1.09	SG	CM
Grade 300 Averages			300	337	1.12	-------	-------

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.
G: Break of less than all seven strands in the grips.
CM: Clear break of all seven strands in the middle of the specimen.
CG: Clear break of all seven strands near the grips.

Both the Grade 270 and Grade 300 strands easily surpassed their minimum required ultimate breaking stresses. In fact, they both averaged over 30 ksi (0.167 square in. x 30 ksi or 5 kips) higher than the minimum requirement. For the Grade 270 strands, the average breaking stress of the five strands was 304 ksi (50.8 kips), with three of the strands failing with clear breaks. This coincides with a tested breaking stress 12.6 per cent higher than required. The results of Grade 300 super strands were comparable to those of the Grade 270 super strands. For example, the Grade 300 super strands averaged 12.3 per cent higher than their minimum breaking stress, almost identical to the results of the Grade 270 super strands tested in the same manner. Their average tested breaking strength was 337 ksi (56.3 kips), with four of the six strands failing with clear breaks.

The last set of strands analyzed were the Grade 270, 0.6 in. diameter, 0.217 square in. area strands shown in Table 4.6. With no Grade 300 counterpart available at the time of this research, comparisons to the Grade 300 strand may be a source of future research.

Table 4.6: Breaking Stress Analysis of Grade 270, 0.6 in. Diameter Strand

Grade	Diameter (in.)	Area (in.^{2})	Minimum Ultimate Breaking Stress Req'd (ksi)	Ultimate Breaking Stress Tested (ksi)	Ratio: fpu Tested / fpu Req'd	Type of Grips	Type of Break
270	0.6	0.217	270	277	1.03	AF	G
270	0.6	0.217	270	273	1.01	AF	G
270	0.6	0.217	270	316	1.17	SG	G
270	0.6	0.217	270	316	1.17	SG	G
270	0.6	0.217	270	314	1.16	SG	G
270	0.6	0.217	270	314	1.16	SG	G
270	0.6	0.217	270	315	1.17	SG	CG
Averages			270	304	1.12	-------	-------

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.
G: Break of less than all seven strands in the grips.
CM: Clear break of all seven strands in the middle of the specimen.
CG: Clear break of all seven strands near the grips.

The Grade 270, 0.6 in. diameter, regular area strand surpassed the minimum required breaking stress on average by 12.4 per cent. Strand tested using aluminum foil and V-grips averaged a breaking stress of 275 ksi (59.7 kips). This is almost identical to the stress obtained using aluminum foil for the 0.5 in. diameter strand, which had an average breaking stress of 273 ksi. Meanwhile, strand tested using the aluminum inserts, aluminum oxide and V-grips averaged a breaking strength of 315 ksi (68.4 kips). This was again comparable to the 0.5 in. diameter strand in super grips, which averaged 320 ksi.

There was an obvious difference in the results based on the gripping technique. While only one of the four strands tested with the special grips ended up with a clear break, neither of the two with aluminum foil ended up with a clear break. Furthermore, the tested breaking stress of the strands wrapped in special grips averaged 16.7 per cent higher than the minimum guaranteed breakings stress; the strands wrapped with aluminum foil that actually passed the ASTM requirements only averaged 1.9 per cent higher.

4.1.3: Yield Stress

As explained in Chapter Two, the yield point is not calculated the same as in ordinary steel, which has a clearly defined yield plateau. Instead, the yield stress is defined as the strand stress at an extension of 1 per cent. The method used to determine the yield stress is explained in Chapter Three. The yield stress for some of the strand was found through extrapolation. In many cases, the extensometer was removed from the strand immediately after the strand met the minimum required yield stress requirement. As a result, the strand did not always reach the full 1 per cent extension while the extensometer was on the strand. To approximate the actual yield stress of the strand, the stress-strain curve was assumed to be linear, and the average change in strain per second was added to the last extensometer reading until a 1 per cent extension was obtained. This technique was necessary, because an extensometer was damaged early in the testing process as a result of a premature break; subsequently, extra care was taken with the use of the remaining extensometer.

4.1.3.1: Yield Stress Results

ASTM A416 (2005) states that the minimum yield stress should be 90 per cent of the ultimate stress for low-relaxation strand. For the initial set of tests involving the Grade 270, 0.5 in. diameter, 0.153 square in. area strand, every strand tested above the 90 per cent of ultimate stress ASTM requirement. The average yield stress for the strand was 259 ksi (39.6 kips), above the minimum required yield stress of 243 ksi (37.2 kips). The stress-strain curves for the six tests are shown in Figure 4.6.

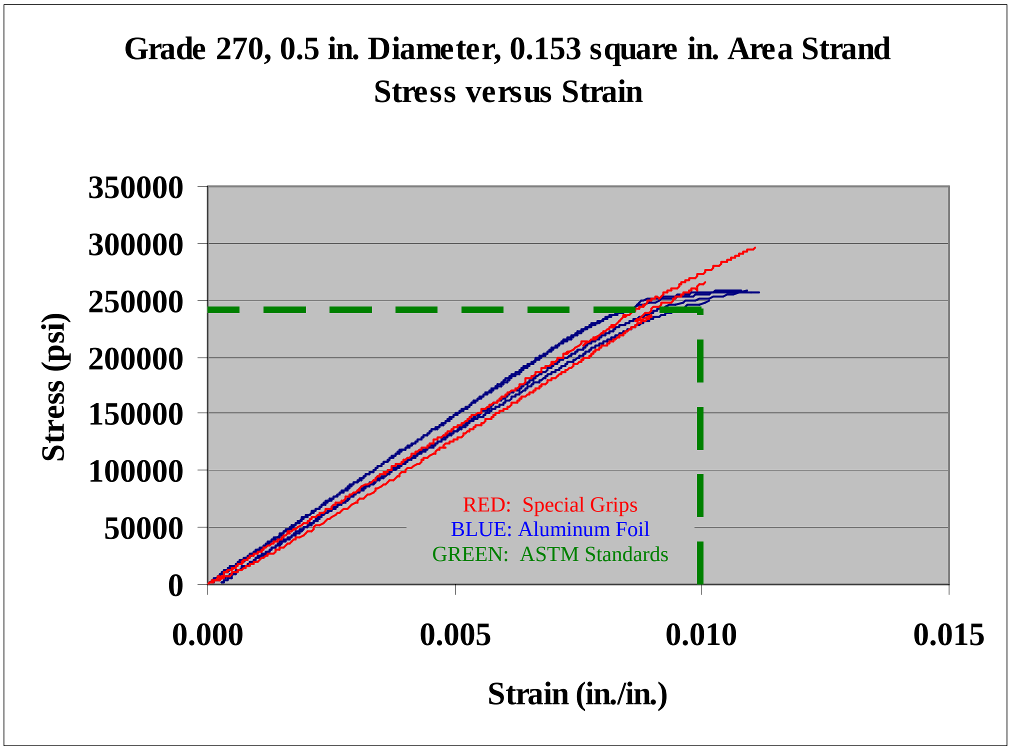

Figure 4.6: Stress-Strain Curves, Grade 270, 0.5 in. Diameter, Regular Strand

The six Grade 300 strands with a 0.5 in. diameter and area of 0.153 square in. also met the ASTM requirements for yield stress. The average yield stress was 281 ksi (42.2 kips), well above the minimum specified yield stress of 270 ksi (41.3 kips). The stress-strain curves for the six tested strands are shown in Figure 4.7.

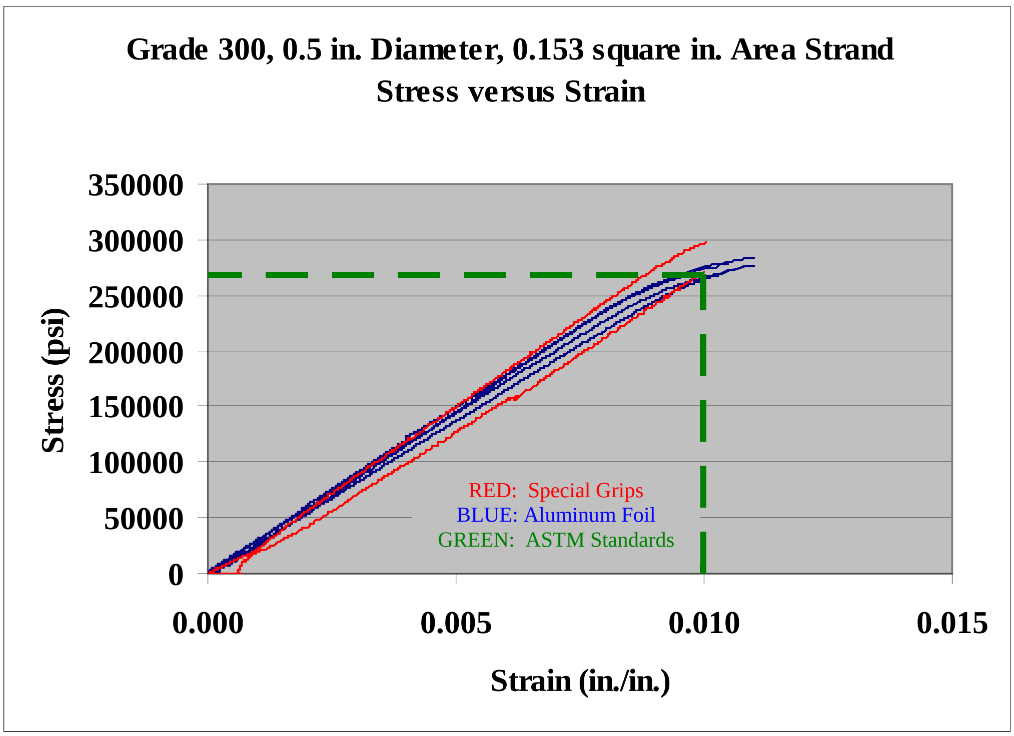

Figure 4.7: Stress-Strain Curves, Grade 300, 0.5 in. Diameter, Regular Strand

The average yield stress for the Grade 270, 0.5 in. diameter, 0.167 square in. area strand was 263.6 ksi (44 kips). Due to concern over the extensometer and the relatively higher than anticipated yield stress, all five of the yield stresses were extrapolated. The extensometer was removed as the strand outperformed the ASTM requirement of 243 ksi (40.6 kips). The highest yield stress was calculated at 277 ksi (46.3 kips), while the lowest was 248 ksi (41.4 kips). The stress-strain curves for the five Grade 270 super strands are displayed in Figure 4.8.

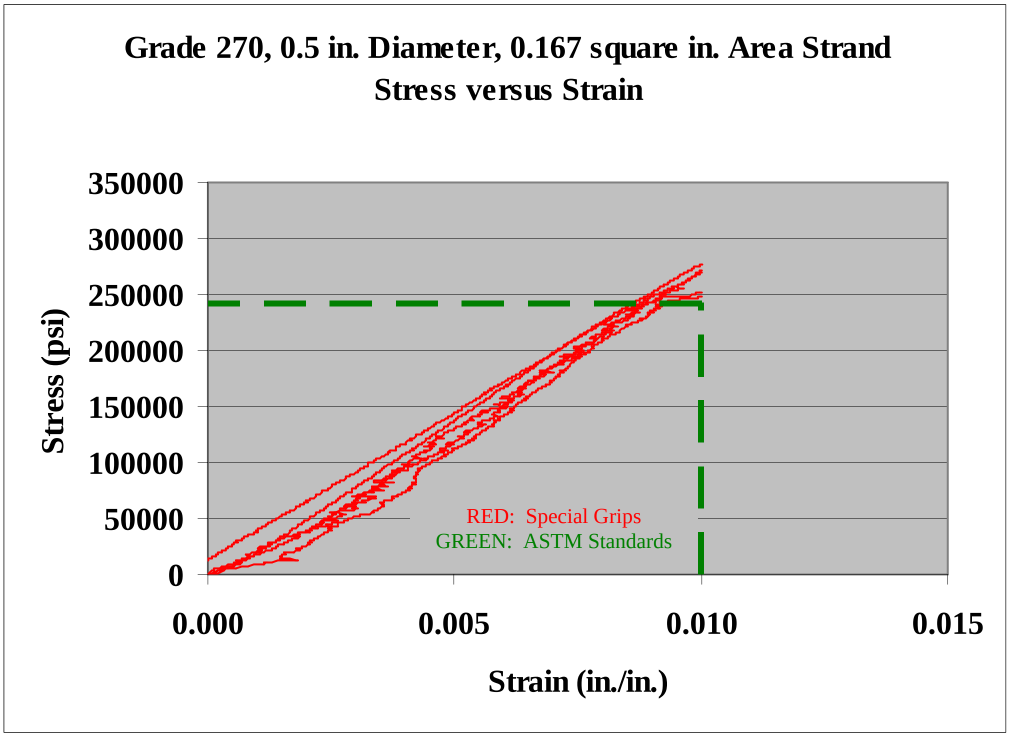

Figure 4.8: Stress-Strain Curves, Grade 270, 0.5 in. Diameter, Super Strand

Six Grade 300, 0.5 in. diameter, 0.167 square in. area strands were tested for yield stress. Four of the six results were extrapolated; the other two were recorded directly from the extensometer. The average yield stress of the six strands was 285.2 ksi (47.6 kips), well above the minimum ASTM required yield stress of 0.9 times 300 ksi, or 270 ksi. The lowest yield stress of the six tested strands was 272 ksi (45.4 kips), while the highest of the six strands was measured at 292 ksi (48.8 kips). The resulting curves are displayed in Figure 4.9.

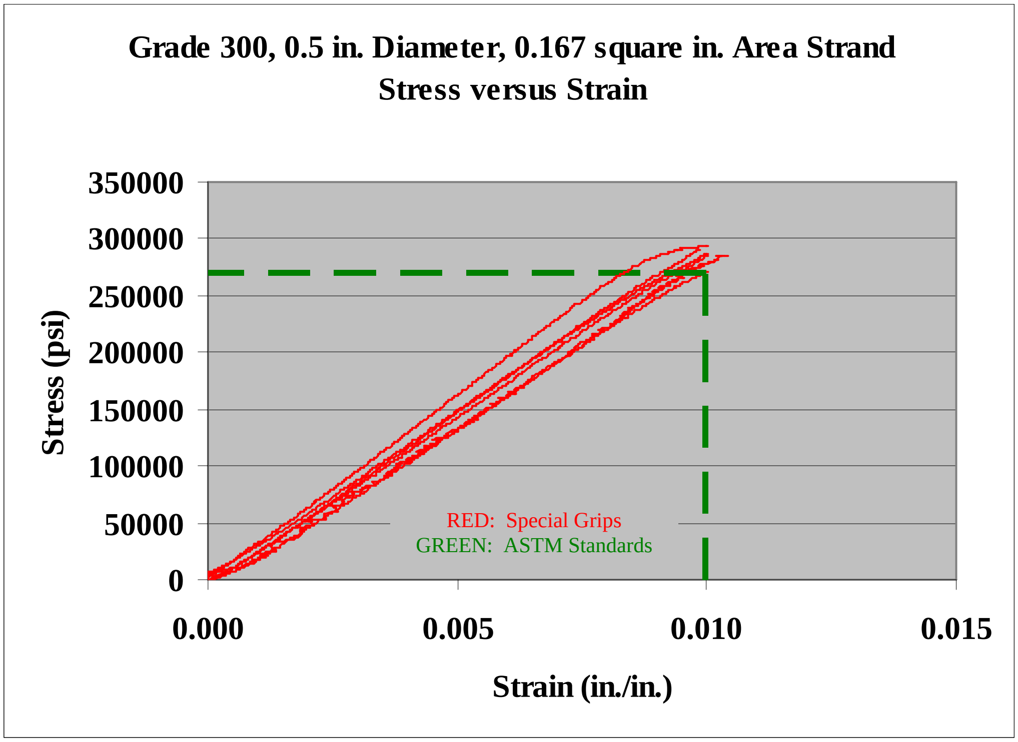

Figure 4.9: Stress-Strain Curves, Grade 300, 0.5 in. Diameter, Super Strand

The stress-strain curves for the seven tested Grade 270, 0.6 in. diameter, 0.217 square in. area strands are shown in Figure 4.10. All seven strands met the ASTM A416 (2005) yield strength requirement of 52,740 lb. Three strands were measured with the extensometer directly, while the other four were extrapolated from the extensometer data. The average yield stress of the Grade 270, 0.6 in. diameter, 0.217 square in. area strands was 274 ksi (59.5 kips). While higher than anticipated, it does correlate with the notion that strand yields at approximately 90 per cent of its ultimate stress. For example, the average tested ultimate stress was 303 ksi (65.8 kips). Taking 90 per cent of 303 ksi (65.8 kips) would require a yield stress of 273 ksi (59.2 kips), which is approximately equal to the average yield stress of 274 ksi (59.5 kips).

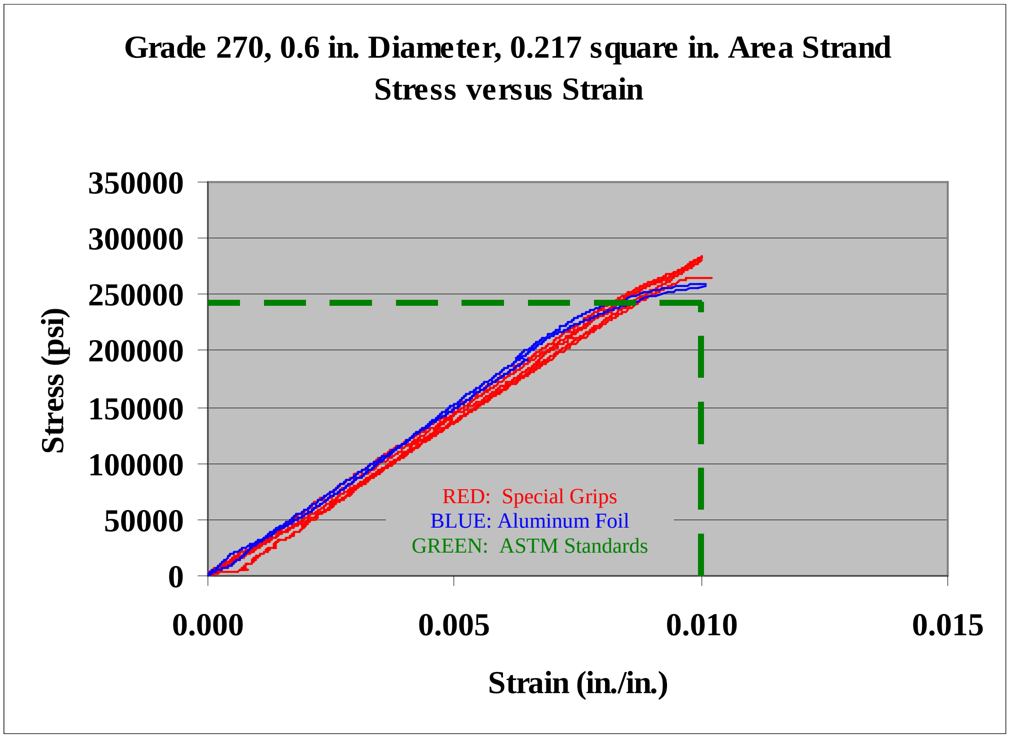

Figure 4.10: Stress-Strain Curves, Grade 270, 0.6 in. Diameter, Regular Strand

4.1.3.2: Yield Stress Analysis

Every strand tested was manufactured to meet the minimum guaranteed yield stress outlined in ASTM A416 (2005), meaning that all of the strand yielded at or beyond 90 per cent of the minimum guaranteed breaking stress. Some of the specimens yielded just at or above the advertised yield stress. In other tests, the strands easily surpassed the minimum requirement by more than 15 per cent. There was a correlation between yield stress and the type of grip used, although not as significant as it was with the ultimate breaking stress tests.

The first strands analyzed and compared were the Grade 270 and Grade 300, 0.5 in. diameter, 0.153 square in. area strands shown in Table 4.7.

Table 4.7: Yield Stress Analysis of 0.5 in. Diameter, Regular Strand

Grade	Diameter (in.)	Area (in.^{2})	Actual Tested Yield Stress (ksi)	Min Req'd Yield Stress (ksi)	Ratio: Tested Yield Stress to Required Ultimate Stress	Ratio: Tested Yield to Req'd Yield	Grips
270	0.5	0.153	249	243	0.92	1.02	AF
270	0.5	0.153	258	243	0.96	1.06	AF
270	0.5	0.153	255	243	0.94	1.05	AF
270	0.5	0.153	257	243	0.95	1.06	AF
270	0.5	0.153	273	243	1.01	1.12	SG
270	0.5	0.153	265	243	0.98	1.09	SG
Grade 270 Averages			260	243	0.96	1.07	-------
300	0.5	0.153	277	270	0.91	1.03	AF
300	0.5	0.153	278	270	0.91	1.03	AF
300	0.5	0.153	277	270	0.91	1.03	AF
300	0.5	0.153	284	270	0.93	1.05	AF
300	0.5	0.153	270	270	0.78	1.00	SG
300	0.5	0.153	298	270	0.84	1.10	SG
Grade 300 Averages			281	270	0.94	1.04	-------

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.

The tested Grade 270, 0.5 in. diameter, regular area strands surpassed the required yield stress by an average of 6.7 per cent. Averaging 96 per cent of their required breaking stress, one strand even exceeded the minimum required breaking stress (270 ksi) with a yield stress of 273 ksi. The aluminum foil gripped strands yielded at a 5.75 per cent lower stress than the strands wrapped with the special grips, although all of the stresses were above the required yield stress.

When analyzing the yield stress results for the Grade 300, 0.5 in. diameter, regular area strands, there was little differentiation in the results based on grips used. While the maximum yield stress did occur while using special grips, the minimum yield stress also occurred while using the special grips. On average, the special grip and aluminum foil gripped strands yielded 4.7 per cent and 3.5 per cent above the minimum required yield stress, respectively, for an overall ratio of 1.04 (or 4 per cent higher) when comparing actual yield stress to minimum required yield stress.

The next strands analyzed were the Grade 270 and Grade 300 super area strands shown in Table 4.8. With premature breaks for super strand wrapped in aluminum foil, numerical comparisons between grip types were unavailable.

Table 4.8: Yield Stress Analysis of 0.5 in. Diameter, Super Area Strand

Grade	Diameter (in.)	Area ($in.^2$)	Actual Tested Yield Stress (ksi)	Min Req'd Yield Stress (ksi)	Ratio: Tested Yield Stress to Required Ultimate Stress	Ratio: Tested Yield to Req'd Yield	Grips
270	0.5	0.167	248	243	0.92	1.02	SG
270	0.5	0.167	277	243	1.03	1.14	SG
270	0.5	0.167	252	243	0.93	1.04	SG
270	0.5	0.167	269	243	1.00	1.11	SG
270	0.5	0.167	272	243	1.01	1.12	SG
Grade 270 Averages			264	243	0.98	1.08	-------
300	0.5	0.167	287	270	0.96	1.06	SG
300	0.5	0.167	285	270	0.95	1.06	SG
300	0.5	0.167	295	270	0.98	1.09	SG
300	0.5	0.167	278	270	0.93	1.03	SG
300	0.5	0.167	294	270	0.98	1.09	SG
300	0.5	0.167	272	270	0.91	1.01	SG
Grade 300 Averages			285	270	0.95	1.06	-------

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.

Special grips were used on all of the super strands. The Grade 270 super strands yielded 8.6 per cent higher than required, and the Grade 300 super strands yielded 5.7 per cent higher then required. Comparing the tested yield stresses to their required breaking stresses, the strands performed almost identically, with the Grade 270 average ratio at 0.98 compared to the Grade 300 average ratio of 0.95. When analyzing all of the 0.5 in. diameter strands wrapped with the special grips, the performance of tested yield to required yield was also almost the same. The Grade 270 and Grade 300, 0.5 in. diameter, regular area strands averaged yielding 7.7 per cent above required yield; meanwhile, the Grade 270 and Grade 300, 0.5 in. diameter, super area strands averaged yielding 7.0 per cent above required yield.

Finally, the Grade 0.6 in. diameter, 0.167 square in. area strands were analyzed; a breakdown analyzing the yield stress of the seven tested strands is shown in Table 4.9.

Table 4.9: Yield Stress Analysis of 0.6 in. Diameter Strand

Grade	Diameter (in.)	Area (in.^{2})	Actual Tested Yield Stress (ksi)	Min Req'd Yield Stress (ksi)	Ratio: Tested Yield Stress to Required Ultimate Stress	Ratio: Tested Yield to Req'd Yield	Grips
270	0.6	0.217	260	243	0.96	1.07	AF
270	0.6	0.217	261	243	0.97	1.07	AF
270	0.6	0.217	280	243	1.04	1.15	SG
270	0.6	0.217	283	243	1.05	1.16	SG
270	0.6	0.217	283	243	1.05	1.16	SG
270	0.6	0.217	284	243	1.05	1.17	SG
270	0.6	0.217	265	243	0.98	1.09	SG
Averages			274	243	1.01	1.13	-------

Key
AF: Aluminum foil and V-grips used to grip the strand.
SG: Special grips (aluminum tubing, aluminum oxide, and V-grips) on the strand.

While the yield stresses shown in Table 4.9 were much higher than the minimum required, their tested yield stress still averaged approximately 90 per cent of the tested ultimate stress. The two aluminum foil wrapped strands both yielded 7 per cent above the required yield stress. The five special grip wrapped strands yielded more than two times higher than the aluminum foil wrapped strands, by yielding 14.6 per cent above the minimum required yield stress.

4.1.4: Modulus of Elasticity Results and Analysis

The modulus of elasticity was measured from the stress versus strain data and plots produced by the extensometer (measuring strain) and the MTS 407 (measuring load). Modulus of elasticity is not addressed in ASTM A416 (2005) or ASTM A370 A7 (2005). While briefly addressed in various texts and design aids, the recommended values vary from source to source. Unless more precise data is available, the PCI Design Handbook (1999) and the AASHTO LRFD Bridge Design Specification (2004) suggest using a modulus of elasticity of 28,500 ksi. In the book Design of Highway Bridges (Barker and Puckett 1997), the recommended value for modulus of elasticity is 197,000 MPa (28,570 ksi). However, in the book Design of Prestressed Concrete (Nilson 1987), the recommended value for modulus of elasticity is 27,000 ksi for strand. From 188 test results provided by Ronald Mann (mailed spreadsheets 2005), the range of the modulus of elasticity for testing conducted at Strand Tech ranged from 28,200 ksi to 30,400 ksi. In a draft of Training for the Testing of Prestressing Steel Strand by the Prestressing Steel Committee (2005), they estimate the typical range for modulus of elasticity to be 28,000 ksi to 29,200 ksi. However, they also note that the actual modulus of elasticity is usually contracted between the manufacturer and the engineer (Prestressing Steel Committee 2005).

Calculations for this testing were made using Hooke's Law shown in Equation 4.1 (Boresi and Schmidt 2003), where the moduli of elasticity is the slope of the linear portion of the stress-strain curve.

$$\sigma = E\varepsilon \qquad \textbf{(4.1)}$$

where:

σ = tensile stress (ksi)

E = modulus of elasticity (ksi)

ε = strain (in./in.)

The low point of the proportional region was established as the point at which the strand reached 10 per cent of its minimum breaking strength. For example, for a Grade 270, 0.5 in. diameter, 0.153 square in. area strand, the low point would be considered 27 ksi (270 ksi times 10 per cent times 0.153 square in, or 4.1 kips). This was done to eliminate error caused by slack in the strand and seating slip between the grips and strand.

The modulus of elasticity results were as expected. There was an overall average of 28,900 ksi and range of 27,100 ksi to 30,400 ksi. The modulus of elasticity of the Grade 270 and Grade 300 strand were strikingly similar. For example, when comparing the 0.5 in. diameter, 0.153 square in. area strands, the average modulus of elasticity for the Grade 270 strand was 28,400 ksi compared to 28,600 ksi for the Grade 300 strand. Meanwhile, the Grade 270 and Grade 300 super strands had identical average modulus of elasticity values of 29,300 ksi. The modulus of elasticity of the Grade 270, 0.6 in. diameter strand averaged to 28,800 ksi.

Table 4.10: Modulus of Elasticity Results

Grade	Diameter (in.)	Area (in.^{2})	E (ksi)	Grips
270	0.5	0.153	27300	AF
270	0.5	0.153	29700	AF
270	0.5	0.153	29400	AF
270	0.5	0.153	28400	AF
270	0.5	0.153	27700	SG
270	0.5	0.153	28000	SG
GR 270, 0.5 in. Diameter, Regular Average			28400 ksi	
300	0.5	0.153	27100	AF
300	0.5	0.153	28000	AF
300	0.5	0.153	28300	AF
300	0.5	0.153	29500	AF
300	0.5	0.153	28300	SG
300	0.5	0.153	30200	SG
GR 300, 0.5 in. Diameter, Regular Average			28600 ksi	
270	0.5	0.167	29100	SG
270	0.5	0.167	29000	SG
270	0.5	0.167	28900	SG
270	0.5	0.167	29600	SG
270	0.5	0.167	30000	SG
GR 270, 0.5 in. Diameter, Super Average			29300 ksi	
300	0.5	0.167	28700	SG
300	0.5	0.167	29000	SG
300	0.5	0.167	30300	SG
300	0.5	0.167	28100	SG
300	0.5	0.167	30400	SG
300	0.5	0.167	29100	SG
GR 300, 0.5 in. Diameter, Super Average			29300 ksi	
270	0.6	0.217	29900	AF
270	0.6	0.217	28700	AF
270	0.6	0.217	28500	SG
270	0.6	0.217	29700	SG
270	0.6	0.217	28600	SG
270	0.6	0.217	28400	SG
270	0.6	0.217	28100	SG
GR 270, 0.6 in. Diameter, Regular Average			28800 ksi	

Key

AF: Aluminum foil grips   SG: Special grips (tubing and aluminum oxide)

There was little to no impact on the modulus of elasticity results when comparing strands wrapped with aluminum foil versus strands wrapped with the special grips. Overall, the aluminum foil strands averaged a modulus of elasticity of 28,600 ksi, while the strands with special grips averaged 29,000 ksi. An immediate look at these numbers suggests that the grips impacted the outcome of the modulus of elasticity. However, as demonstrated in Table 4.10, the strands wrapped with aluminum foil actually had a higher modulus of elasticity average when used with the Grade 270, 0.5 in. diameter, regular area strands (28,700 ksi versus 27,900 ksi) and the Grade 270, 0.6 in. diameter, regular area strands (29,300 ksi versus 28,700 ksi).

A closer analysis would suggest that the super strands may have a higher modulus of elasticity than the regular area strands. The twelve 0.5 in. diameter regular area strands averaged 28,500 ksi compared to 29,300 ksi for the eleven 0.5 in. diameter super strands tested.

4.1.5: Elongation Results and Analysis

The elongation properties of strand are an indication of the strand's ductility. Prestressing strand, a highly ductile material, can exhibit large elongations. ASTM A416 (2005) requires the total strand elongation to be greater than or equal to 3.5 per cent using a gage length of 24 in. The testing methods used for this testing are explained in Chapter 3. Total elongation was measured by combining the 1 per cent elongation measured by the extensometer with the change in SATEC crosshead movement from the time the extensometer was removed until the strand ruptured. Results and analysis for the 30 strands tested are shown in Table 4.11.

Table 4.11: Elongation Results and Analysis

Grade	Diameter (in.)	Area (in.^{2})	Elongation (%)	Grips	Break
270	0.5	0.153	4.6%	AF	G
270	0.5	0.153	7.2%	AF	G
270	0.5	0.153	7.4%	AF	G
270	0.5	0.153	7.8%	AF	G
270	0.5	0.153	8.3%	SG	CM
270	0.5	0.153	8.6%	SG	CM
GR 270, 0.5 in. Dia., Regular Average			7.3% average total elongation		
300	0.5	0.153	5.6%	AF	G
300	0.5	0.153	6.3%	AF	G
300	0.5	0.153	8.6%	AF	G
300	0.5	0.153	7.2%	AF	G
300	0.5	0.153	9.4%	SG	CM
300	0.5	0.153	8.5%	SG	CM
GR 300, 0.5 in. Dia., Regular Average			7.6% average total elongation		
270	0.5	0.167	7.7%	SG	CM
270	0.5	0.167	6.8%	SG	CM
270	0.5	0.167	7.4%	SG	G
270	0.5	0.167	7.4%	SG	CG
270	0.5	0.167	6.2%	SG	G
GR 270, 0.5 in. Dia., Super Average			7.1% average total elongation		
300	0.5	0.167	7.2%	SG	G
300	0.5	0.167	7.9%	SG	CM
300	0.5	0.167	7.4%	SG	CG
300	0.5	0.167	7.2%	SG	G
300	0.5	0.167	7.9%	SG	CM
300	0.5	0.167	7.3%	SG	CM
GR 300, 0.5 in. Dia., Super Average			7.5% average total elongation		
270	0.6	0.217	7.6%	AF	G
270	0.6	0.217	5.7%	AF	G
270	0.6	0.217	6.5%	SG	G
270	0.6	0.217	6.8%	SG	G
270	0.6	0.217	6.1%	SG	G
270	0.6	0.217	7.1%	SG	G
270	0.6	0.217	7.5%	SG	CG
GR 270, 0.6 in. Dia., Regular Average			6.8% average total elongation		

Key AF: Aluminum foil. SG: Special grips (tubing and aluminum oxide).
G: Break in grips. CM: Clear break in the middle. CG: Clear break near the grips.

Equation 4.2 shows the equation used to calculate the elongation of a strand.

$$Percent\ Elongation = \frac{L_f - L_o}{L_o} \times 100\% \qquad \textbf{(4.2)}$$

where:

L_f = final displacement of the extensometer (in.)

L_o = original gage length of the extensometer (in.)

The 188 elongation readings provided by Ronald Mann (mailed spreadsheets 2005) from Strand Tech Martin, Inc. revealed a range of elongation values from 4.02 per cent to 8.27 per cent for a variety of strands. Each strand tested for this research passed the ASTM A416 (2005) 3.5 per cent minimum elongation, and the results coincided with the values provided by Strand Tech.

With modulus of elasticity values higher for the super strands than the regular strands shown in Section 4.1.4, expectations were that the elongation values for the super strands would be slightly lower than those of the regular area strands. In fact, that is exactly what happened. The 0.5 in. diameter, 0.153 square in. area strands for the Grade 270 and Grade 300 strands averaged 7.3 and 7.6 per cent elongation, respectively. Meanwhile, the Grade 270 and Grade 300, 0.5 in. diameter, super strands averaged 7.1 and 7.5 per cent elongation, respectively. Finally, the Grade 270, 0.6 in. diameter, regular strand averaged 6.8 per cent elongation.

Two other correlations were seen in the elongation results. Elongations of strands with the special grips averaged 212.6 per cent higher than the 3.5 per cent minimum elongation (7.5 per cent nominal elongation), compared to 194.3 per cent higher than the minimum for strand with aluminum foil for grips (6.8 per cent nominal elongation). Furthermore, as expected, strand that ultimately failed with a clear break had greater elongation when compared to strand that failed with less than all seven wires breaking simultaneously. The clear break strands averaged a total elongation of 7.9 per cent compared to only 6.8 per cent without the clear break. Elongation is not a concern for the Grade 300 or super area strands. Their ductility characteristics will allow them to deflect extensively before failure.

4.1.6: Analysis of ASTM Cushioning Material Recommendations

Aluminum foil was adequate as a cushioning material for the V-grips when normal area, 0.5 in. diameter strands were tested. However, it was inadequate when testing the larger area super strands. Five tests were conducted (three using Grade 270 super and two using Grade 300 super strands) using aluminum foil as the cushioning material during super strand tension testing. All five strands fractured prematurely to the minimum ultimate breaking stress, with only one wire breaking in the grip.

In every successful tension test that used aluminum foil as a cushioning agent, the strand eventually failed just above the minimum required breaking stress with one or more strands breaking at the grip. In other words, aluminum foil may be used as a cushioning material during a tension test if testing a regular diameter strand, and if the objective is simply to investigate whether the strand will pass the minimum standards. Figure 4.11 portrays a tested Grade 300, 0.5 in. diameter, 0.153 square in. area strand in which five of the seven strands broke in the grips.

Figure 4.11: Break at Grips using Aluminum Foil

Meanwhile, the majority of the strands (12 out of 20) ended up failing with a clear break either in the middle (9 out of 20) or near the grips (3 out of 20) when gripped with the aluminum tubing and aluminum oxide. This is a much better option than the aluminum foil if the goal is to find out the true breaking stress of the strand. Examples of some of the clear breaks from the testing are shown in Figures 4.12 and 4.13.

Figure 4.12: Clear Breaks in Center of Strand

Figure 4.13: Clear Break in Test Machine

4.2: Relaxation Tests Results and Analysis

4.2.1: Introduction to Relaxation Tests

A total of 26 relaxation tests were conducted in order to determine the losses due to relaxation for the various samples of strand. The relaxation tests were completed by following the procedures presented in Chapter 3. This section presents the results and details of these 26 tests. Tables 4.12, 4.13, and 4.14 provide the results of the relaxation testing.

Table 4.12: Relaxation of Grade 270 and 300, 0.5 in. Diameter, Regular Strands

Type	Frame Size	Strand Diameter (in.)	Strand Area (in.^{2})	Duration (hours)	Initial Stress versus f_{pu} (%)	Total Force Loss (%)	Chucks
GR 270	Small	0.5	0.153	1008	59.3%	2.37%	Standard
GR 270	Small	0.5	0.153	1005	62.0%	1.91%	Magnum
GR 270	Small	0.5	0.153	1004	60.6%	2.28%	Magnum
GR 270	Medium	0.5	0.153	1001	67.1%	1.77%	Magnum
GR 270	Medium	0.5	0.153	1001	68.7%	1.23%	Magnum
GR 270	Large	0.5	0.153	215	75.0%	0.68%	Magnum
GR 270	Large	0.5	0.153	264	75.1%	0.87%	Magnum
GR 270	Large	0.5	0.153	200	75.4%	0.99%	Magnum
GR 300	Small	0.5	0.153	1003	59.9%	0.95%	Magnum
GR 300	Small	0.5	0.153	1004	58.6%	1.56%	Magnum
GR 300	Small	0.5	0.153	1011	56.8%	1.77%	Magnum
GR 300	Medium	0.5	0.153	1003	65.1%	1.51%	Magnum
GR 300	Medium	0.5	0.153	1004	67.1%	1.33%	Magnum
GR 300	Large	0.5	0.153	293	81.1%	1.53%	Magnum
GR 300	Large	0.5	0.153	221	74.5%	0.94%	Magnum
GR 300	Large	0.5	0.153	241	73.8%	1.12%	Magnum

Table 4.13: Relaxation of Grade 270 and 300, 0.5 in. Diameter, Super Strands

Type	Frame Size	Strand Diameter (in.)	Strand Area (in.^{2})	Duration (hours)	Initial Stress versus f_{pu} (%)	Total Force Loss (%)	Chucks
GR 270	Medium	0.5	0.167	1009	67.4%	1.09%	Magnum
GR 270	Medium	0.5	0.167	1010	67.3%	1.12%	Magnum
GR 270	Medium	0.5	0.167	1011	65.2%	1.70%	Magnum
GR 300	Medium	0.5	0.167	1007	64.8%	2.43%	Magnum
GR 300	Medium	0.5	0.167	1008	67.4%	1.84%	Magnum
GR 300	Medium	0.5	0.167	1011	68.9%	1.13%	Magnum

Table 4.14: Relaxation of Grade 270, 0.6 in. Diameter Strands

Type	Frame Size	Strand Diameter (in.)	Strand Area (in.^{2})	Duration (hours)	Initial Stress versus f_{pu} (%)	Total Loss of Force (%)	Chucks
GR 270	Medium	0.6	0.217	1007	65.6%	2.47%	Standard
GR 270	Medium	0.6	0.217	1005	65.2%	2.49%	Standard
GR 270	Medium	0.6	0.217	1013	64.1%	2.08%	Standard
GR 270	Large	0.6	0.217	200	69.9%	1.64%	Standard

4.2.2: Relaxation Results

The relaxation properties of the strand were determined by tensioning the strand between 50 and 80 per cent of its breaking strength. Typical prestressing applications call for strand to be tensioned between 70 and 80 per cent of the ultimate breaking strength. Attempts were made to replicate that by tensioning every strand to at least 70 per cent of its breaking strength. As noted in Chapter 3, it was not always possible to tension the strand to that level. In fact, tensioning the strand above 70 per cent only occurred in the large frames. ASTM A416 (2005) recommends monitoring relaxation testing for at least 1,000 hours, although it does allow a shorter 200 hour test if it can be shown through extrapolation that the shorter 200 hour test would provide results similar to the 1,000 hour tests. While the majority of the testing lasted at least 1,000 hours, the testing period in the large frames only lasted 200 hours. As demonstrated in Figures 4.14 and 4.15 that follow, the data from the 200 hour tests showed that the total loss from the 200 hour tests were at or below the average of the 1,000 hour tests. Since little, if any, loss occurred after 200 hours in all of the 1,000 hour tests, the shorter 200 hour tests were considered good.

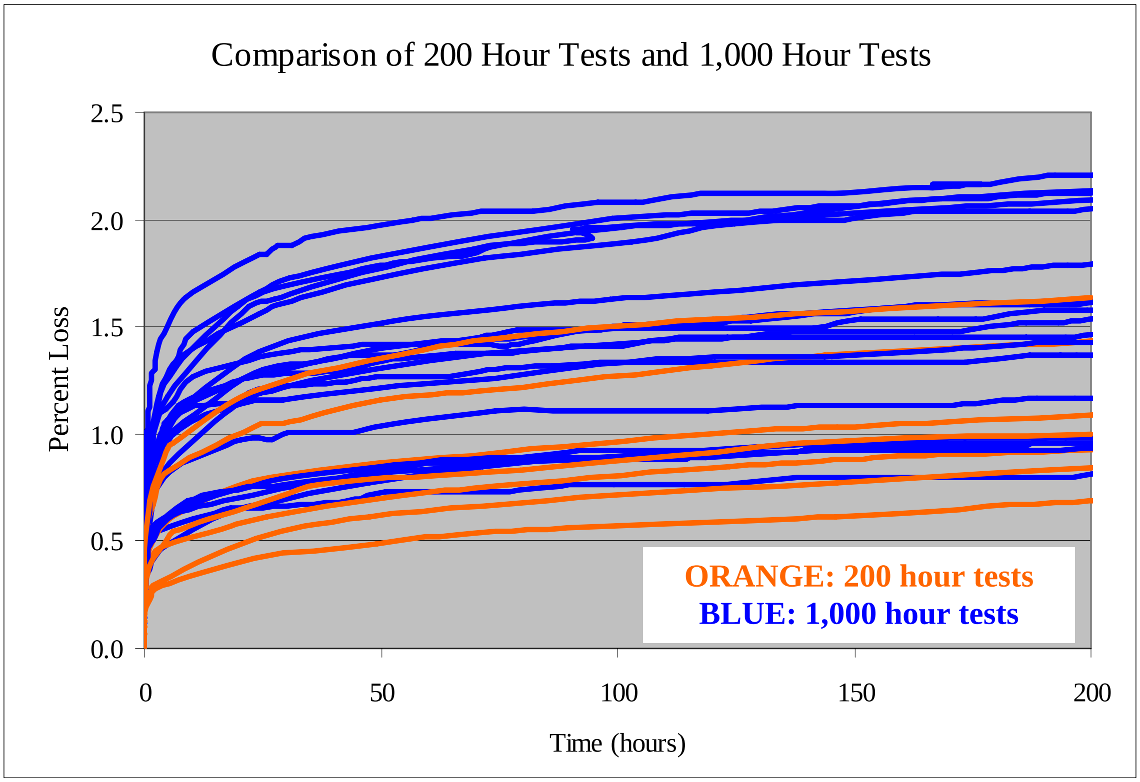

Figure 4.14: Comparison of 200 Hour versus 1,000 Hour Tests at 200 hours

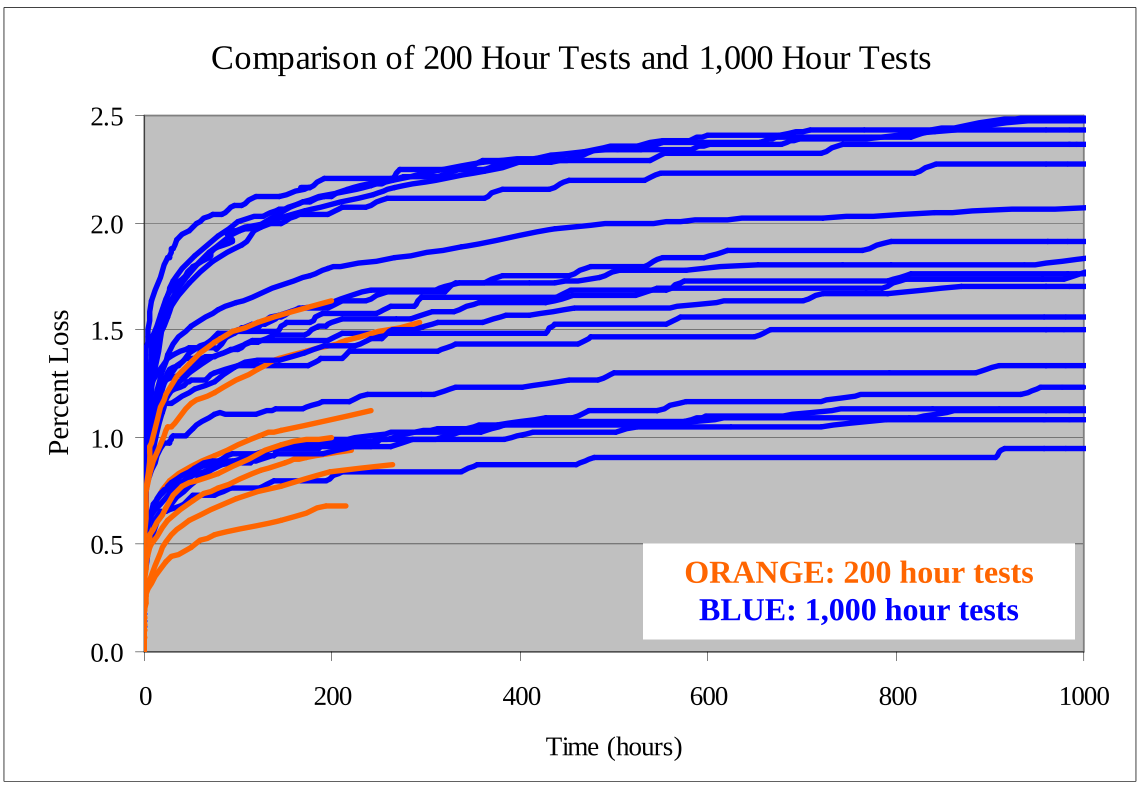

Figure 4.15: Comparison of 200 Hour versus 1,000 Hour Tests at 1,000 hours

The first strands tested were Grade 270, 0.5 in. diameter, 0.153 square in. area strand. The eight strands shown in Figure 4.16 had steel relaxation losses of less than 2.5 per cent when stressed between 50 and 80 per cent of the breaking strength, thus meeting the ASTM A416 (2005) standard. The average percentage relaxation loss for the Grade 270, 0.5 in. diameter, regular strands was 1.51 per cent, slightly conservative to the theoretical predictions of the 2004 and 2005 AASTHO LRFD equations, which predicted 1.71 and 1.52 per cent, respectively. In all of the figures, dashed lines representing the AASHTO LRFD equations assume an initial stress equal to 70 per cent of the strand's breaking stress.

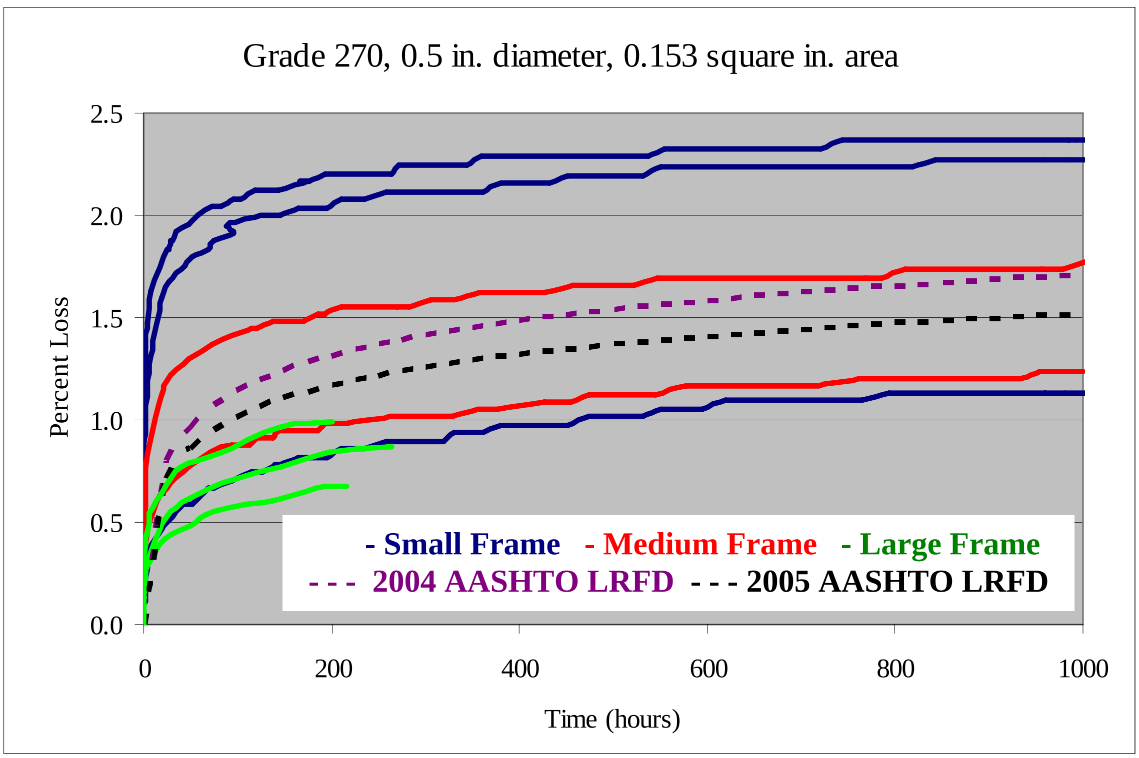

Figure 4.16: Relaxation Curves, Grade 270, 0.5 in. Diameter, Regular Strands

The results from the Grade 270, 0.5 in. diameter, 0.153 square in. area strand relaxation tests provided confidence in the testing procedures. There was little ($\pm$2 microstrain) to no change in the measured strain in the frames throughout the duration of the testing. Furthermore, there was no noticeable change (more than 0.01 of an inch) in the strand length due to chuck slip on either end of the frame.

As a result, testing continued on the Grade 300, 0.5 in. diameter, 0.153 square in. area strand. All of the relaxation results indicated that the strand possessed the relaxation characteristics required in accordance with ASTM A416 (2005). Furthermore, with an average total loss of 1.34 per cent, the relaxation properties for the Grade 300 strand are comparable to those of the Grade 270 strand, which had a 1.51 per cent average total loss. This would also suggest that the 2004 AASHTO LRFD prediction (1.71 per cent) and 2005 AASHTO LRFD prediction (1.52 per cent) of relaxation loss are conservative. A percent loss versus time plot is shown in Figure 4.17.

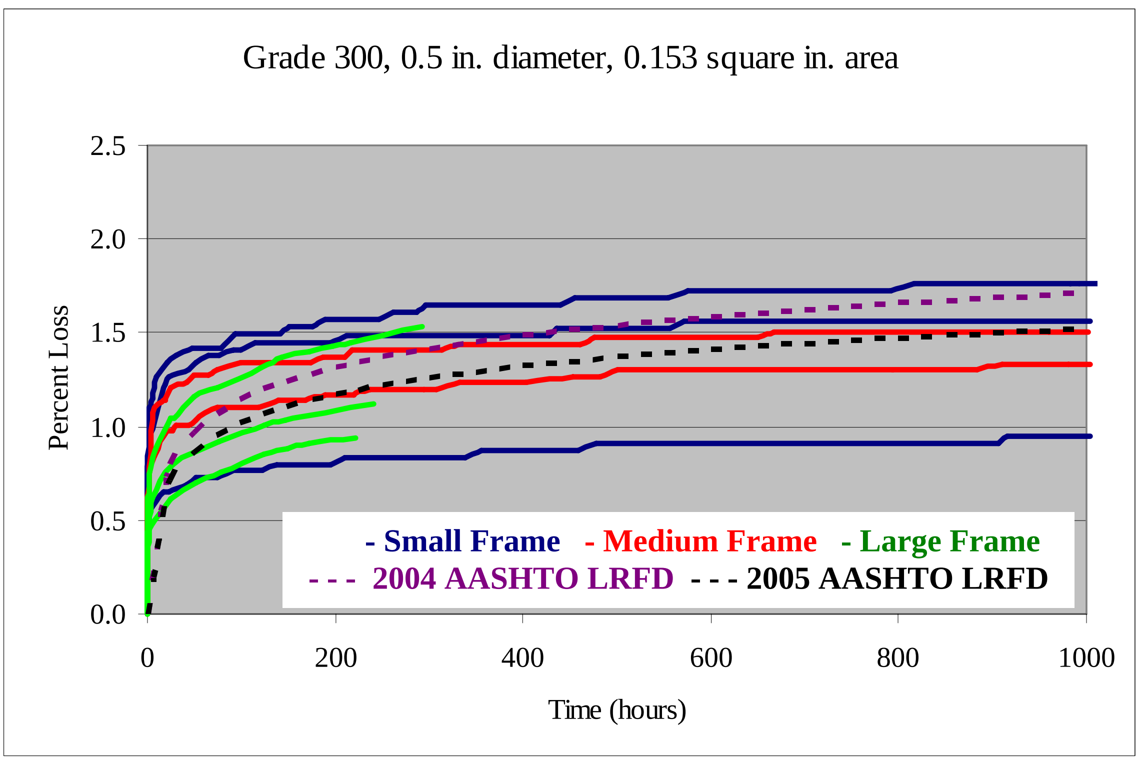

Figure 4.17: Relaxation Curves, Grade 300, 0.5 in. Diameter, Regular Strands

The next set of strands tested was the Grade 270, 0.5 in. diameter, super strands. Three strands were tested in medium frames with magnum chucks. The average relaxation loss for the three Grade 270 super strands was 1.30 per cent, lower than the 2004 and 2005 AASHTO LRFD predicted relaxation losses of 1.52 and 1.71 per cent, respectively, as shown in Figure 4.18.

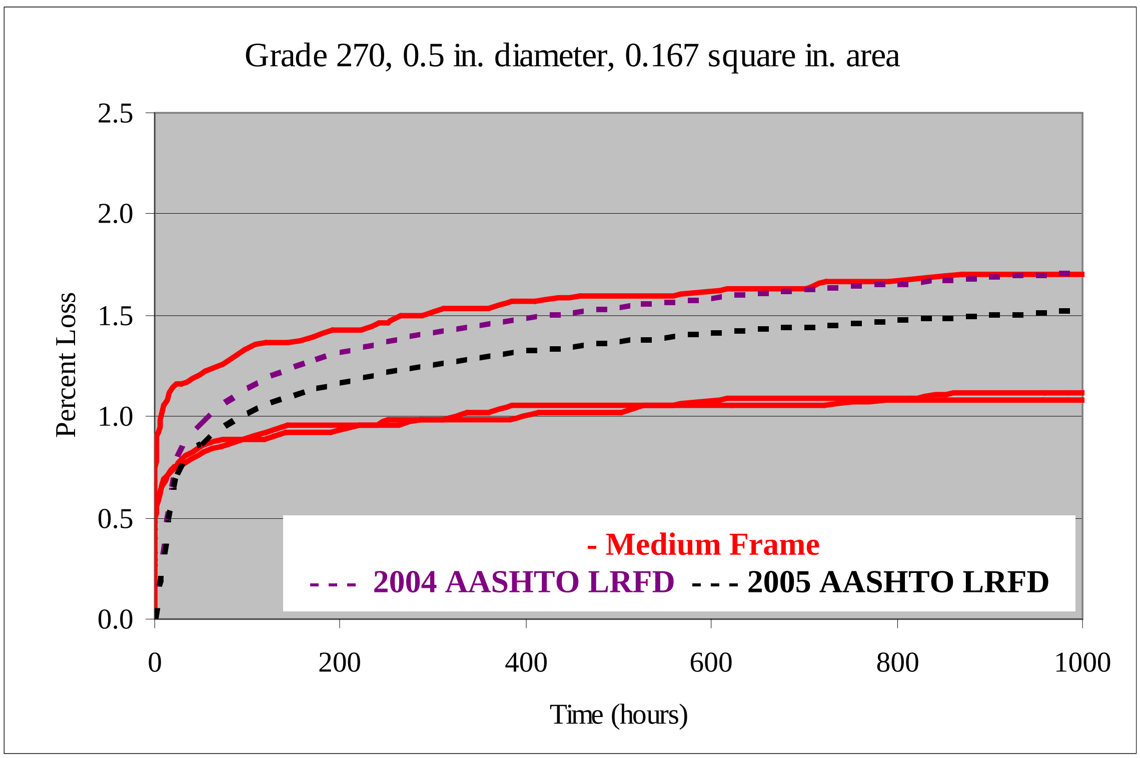

Figure 4.18: Relaxation Curves, Grade 270, 0.5 in. Diameter, Super Strands

Similar to its Grade 270 counterpart, the Grade 300, 0.5 in. diameter, 0.167 square in. super strands shown in Figure 4.19 were tested in medium length frames using magnum chucks. The average percentage relaxation loss for the three Grade 300 super strands was 1.80 per cent, just above the 1.71 per cent loss predicted by the 2004 AASHTO LRFD relaxation loss equation.

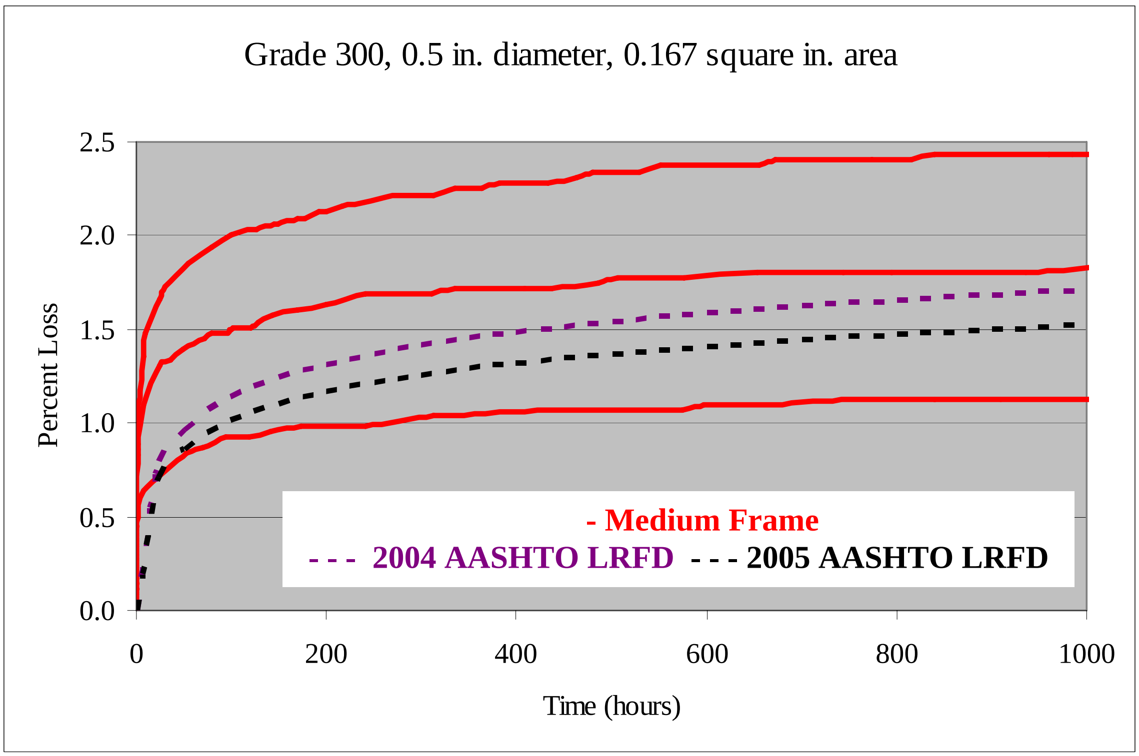

Figure 4.19: Relaxation Curves, Grade 300, 0.5 in. Diameter, Super Strands

Relaxation testing was also done on the Grade 270, 0.6 in. diameter, regular strands. Four strands were tested, with three of the strands tested in the medium length frames, and one strand tested in the long length frame. The average relaxation loss was 2.35 per cent, under the ASTM A416 (2005) limit of 2.5 per cent, but higher than the averages of the other strands tested and the predicted equations offered by AASHTO

LRFD. The plots showing percent loss versus time for the four tested strands are displayed in Figure 4.20. A comparison was unable to be made with a similar diameter Grade 300 strand, due to its unavailability at the time of testing. Nevertheless, the results of the Grade 270, 0.6 in. diameter testing added confidence that the testing procedures used were adequate.

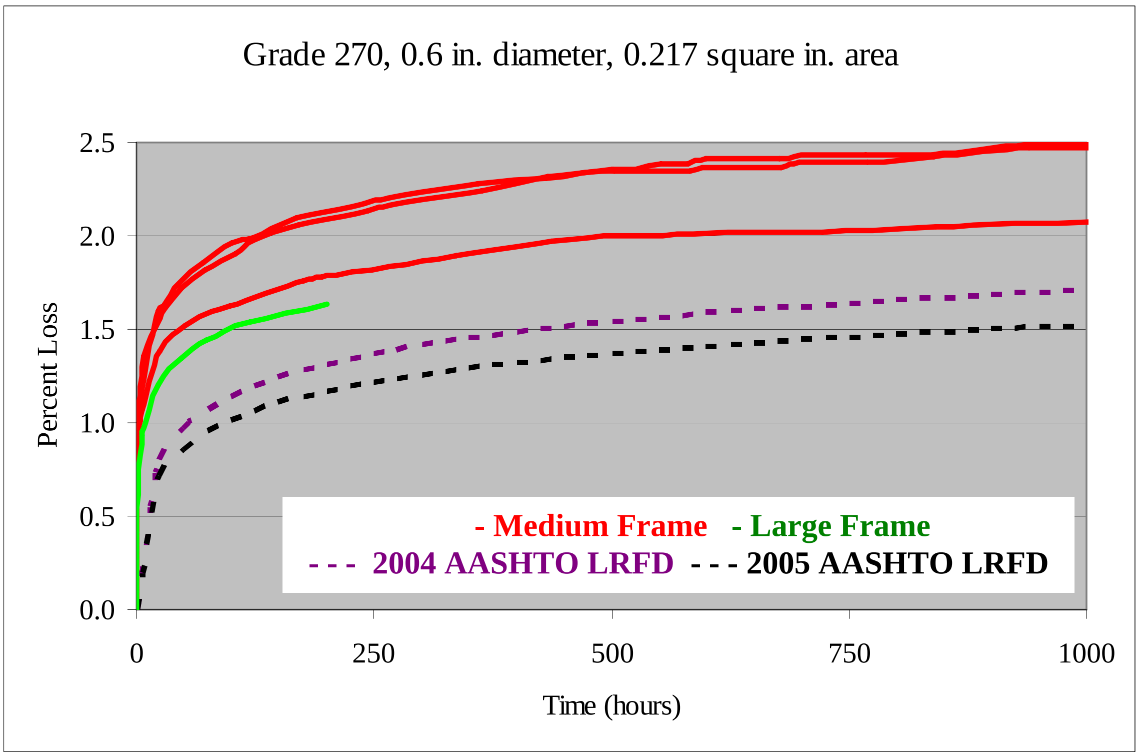

Figure 4.20: Relaxation Curves, Grade 270, 0.6 in. Diameter, Regular Strands

4.2.3: Relaxation Analysis: Impact of Test Length on Results

The main purpose in evaluating the impact of strand test length on the results of relaxation is that there are different standards in different codes internationally as demonstrated in Chapter 2. From the tests conducted for this research, the impact on the relaxation tests was two-fold, as shown in Table 4.15.

Table 4.15: Impact of Test Length on Relaxation Loss

Frame Size	Strand Length (in.)	Number of Tests	Average Initial Stress (% of f_{pu})	Average Total Loss (%)
Small	37.375	6	59.5	1.81
Medium	74.75	13	66.5	1.71
Large	149.5	7	75.0	1.11

First, the length of the strand and frame impacted the amount of stress that could be initially held in the strand. For all strands tested in the small and medium frames, no strand was tensioned to the ASTM A416 (2005) recommended 70 per cent ultimate breaking stress. The test length of the strand changed on the live end of the frame as the actuator released its force to the internal chuck just outside the test frame. This change in length created a higher change in strain for the shorter test lengths, which ultimately resulted in the higher change in stress. The six strands tested in small beds (37-3/8 in. long) could only be stressed to an average of 59.5 per cent of their ultimate stress. In the 13 strands tested in medium beds (74-3/4 in. long), the strands were stressed an average of 66.5 per cent of their ultimate stress. Meanwhile, the seven strands tested in the large frames (149.5 in. long) were tensioned an average of 75.0 per cent. Strands were easily tensioned above 70 per cent of the ultimate stress. In fact, they could actually be tensioned to over 80 per cent of their ultimate stress.

Secondly, there was a correlation between the amount of relaxation and the length of the test specimen. The average loss for strands tested in the small frames was 1.81 per cent at 1,000 hours. Strand tested in the medium frames (twice as long as the small frames) averaged relaxation loss at 1.71 per cent at 1,000 hours. Meanwhile, strand in the long frames (four times as long as the small frames) averaged only 1.11 per cent relaxation loss (at 200 hours). When comparing the actual stress loss of the strands to their 2004 AASHTO LRFD and 2005 AASTHO LRFD equivalents, the small test lengths' average actual stress loss (3.03 ksi) was approximately 114 per cent higher than that predicted by 2004 AASHTO LRFD (1.42 ksi) and 2005 AASHTO LRFD (1.26 ksi). The medium length cut strands averaged 3.17 ksi of relaxation loss, approximately 20 per cent higher than the predicted 2004 AASHTO LRFD loss of 2.65 ksi and 2005 AASHTO LRFD loss of 2.36 ksi. Continuing with the trend, the long length strands were conservative compared to both AASHTO LRFD equations by about a third (2.36 ksi versus 3.59 ksi and 3.19 ksi, respectively). A comparison of the relaxation properties for all 26 strands according to test length is displayed in Figure 4.21.

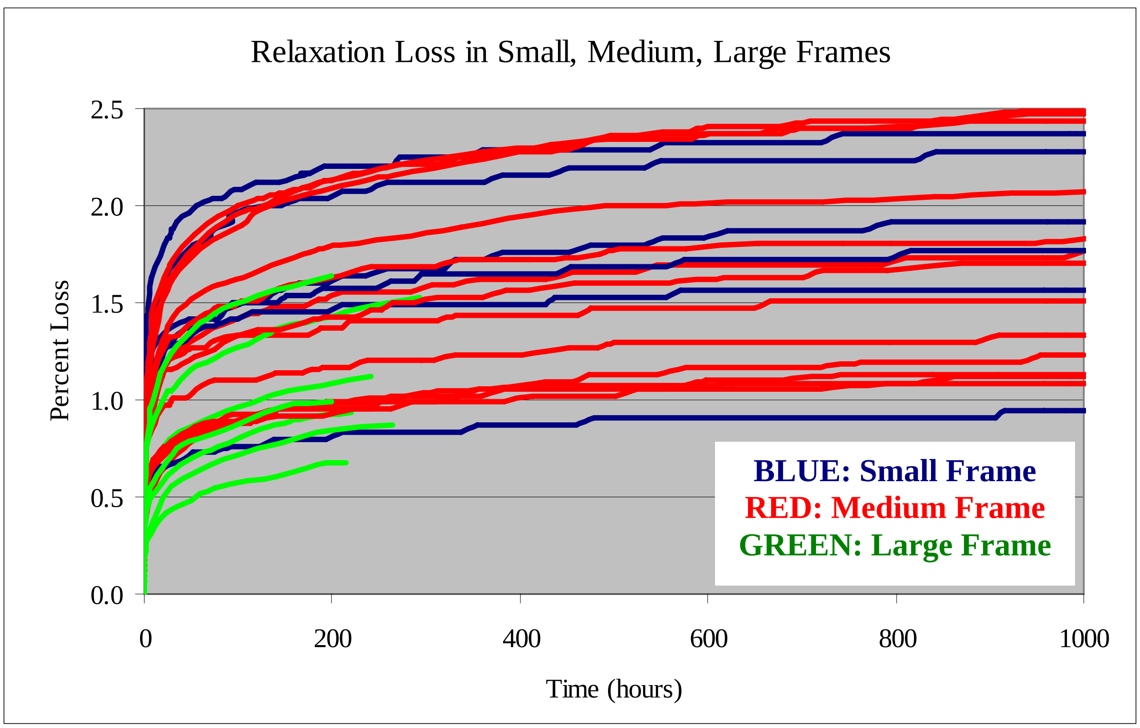

Figure 4.21: Relaxation Loss Comparison: Small, Medium, Large Length Strands

Explanations for both of the relaxation trends discussed include differences in initial levels of stressing, slight seating losses in the chucks, and differences in settling of the system after the pressure in the actuator is released. Of these, the greatest impact lies in the slippage and settling of the chuck frame system. While some of the possible effects causing variability in the results are eliminated since relaxation data is not collected until one minute after the strand is tensioned, the smaller strand test lengths still ended up with more losses than the longer ones. Examples of the amount of loss that can occur by a mere 0.001 in. of slip or settlement on each end of the frame (0.002 in. total) are demonstrated in Table 4.16.

Table 4.16: Impact of Slip and Settlement of Relaxation Bed System on Losses

Strand	Frame Size	Strand Length (in.)	Original Average Jacking Stress (ksi)	Change in Stress due to 0.002 in. Slip/Settlement (ksi)	Losses from Jacking Stress due to Slip/Settlement (%)
Grade 270	Small	37.375	162	1.53	0.94
Grade 300	Small	37.375	180	1.53	0.85
Grade 270	Medium	74.75	175.5	0.76	0.43
Grade 300	Medium	74.75	195	0.76	0.39
Grade 270	Large	149.5	202.5	0.38	0.19
Grade 300	Large	149.5	225	0.38	0.17

Using Hooke's Law from Equation 4.1, the change in stress due to a 0.002 in. change in length of a strand in the small frame (37.375 in. long) is 1.53 ksi. Assuming that the strand is originally tensioned to 60 percent of the ultimate breaking stress (60 per cent times 270 ksi, or 162 ksi), the new stress due to 0.002 in. of slippage and settlement is 160.5 ksi. This amounts to a 0.94 per cent loss in what was measured as total relaxation. Since the accuracy of measurement of slippage on each end of the test frame was 0.005 in., a 0.001 in. change on each end is reasonable and would explain why the smaller test lengths would have more total relaxation loss than the longer test lengths.

As demonstrated with the testing in the small frames, unless a better gripping system is used, the recommendation is to use longer frames. The ASTM A416 (2005) recommendation for a test length of 60 times the nominal diameter is suitable, assuming that the recommended loading criterion of 70 per cent of specified minimum breaking strength can be attained and losses due to chuck slip and frame settlement can be measured and subtracted from the total loss or eliminated altogether in design. If replicating the testing procedures and frames used for this research, the recommended test gage length is that of the larger frame, or 150 inches.

4.2.4: Relaxation Analysis: Impact of Chucks on Results

There was a clear impact on the relaxation results when standard chucks were used compared to when magnum chucks were used. The use of standard chucks in testing resulted in six of the top eight highest relaxation loss percentages, as displayed in Figure 4.22. The longer bodies, meatier teeth, and heavier teeth of the magnum chucks (as described in Section 3.2.1.3) eliminated some of the minute seating losses that impacted the total losses of the strand during the first few minutes of the test. Also of note is that the largest difference in the relaxation loss from one strand to the next is the amount of loss during the first minutes of testing. The tests conducted with the standard chucks lost a great deal more stress in the first minutes of testing than when compared to the tests conducted with magnum chucks. However, within about one hour, every strand relaxation curve began to behave similarly by flattening out, with a sharp decline in the rate of stress loss over time.

Two of the tests using standard chucks in small frames did not even meet the ASTM limit of 2.5 per cent maximum total relaxation loss, with losses over 3 per cent. The two tests that failed involved Grade 270, 0.5 in. diameter, regular area strands. This same strand passed all seven times with an average relaxation loss percentage of only 1.39 per cent when using magnum chucks to hold the tension load in the strand. In fact, the trend of higher relaxation loss for the 0.6 in. diameter strand when compared to the other tested strand is also likely attributable to the fact that standard chucks were used in lieu of magnum chucks. The magnum chucks were unavailable at the time of testing for use with the 0.6 in. diameter strand. While no change was observed when checking for slip at each end using the extensometer, it was clear that using the regular chucks over the magnum chucks with the meatier teeth consistently resulted in higher relaxation losses.

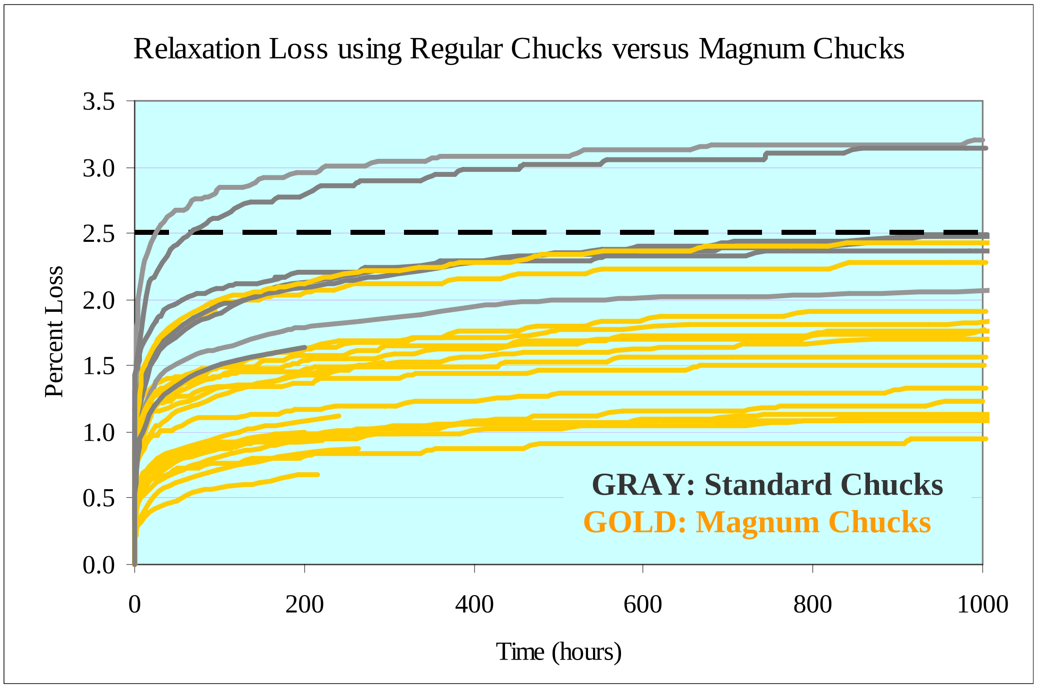

Figure 4.22: Relaxation Curves Comparing Standard and Magnum Chucks

4.2.5: Relaxation Analysis: AASHTO LRFD Relaxation Equation

Due to the differences in the first hours of testing for the same strands, there was a high likelihood of some kind of chuck slip or settling of the frame after tensioning the strand. Furthermore, it appears that the amount of slip or settlement was different in each test.

Figures 4.23 and 4.25 provide another look at the losses when measurements started 1 minute after stressing the strand, as required in accordance with ASTM A416 (2005). Figures 4.24 and 4.26 provide a look at losses when measurements started a full hour after stressing the strand. They provide a comparison to the standard measurements, which were likely affected by chuck slip, frame settlement, and test length.

After one hour of loss, it appears as if the majority of effects of different frame sizes and chuck types are mitigated. The relaxation behavior is more precise in that the total loss curves are much closer together than when compared to tests that began measurements only 1 minute after tensioning. It also reveals that the actual relaxation behavior may be even closer to the 2005 Interim AASHTO LRFD equation than shown by the original data.

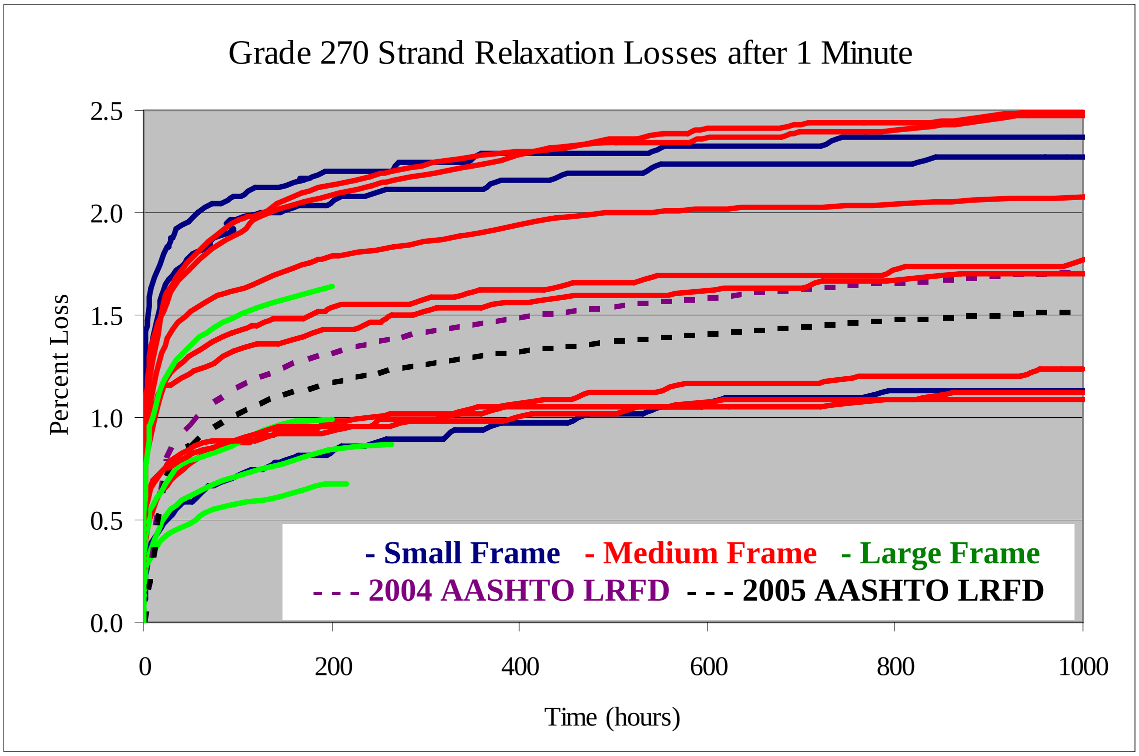

Figure 4.23: Relaxation Loss for Grade 270 Strand Measured after 1 Minute

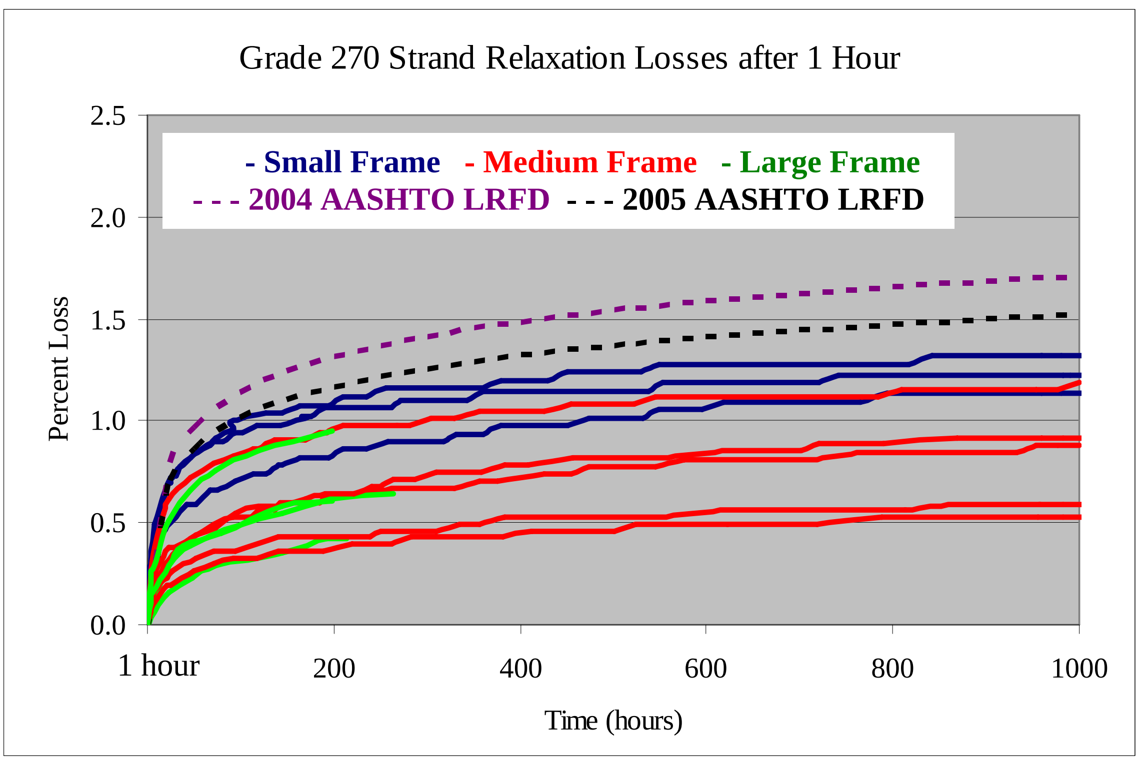

Figure 4.24: Relaxation Loss for Grade 270 Strand Measured after 1 Hour

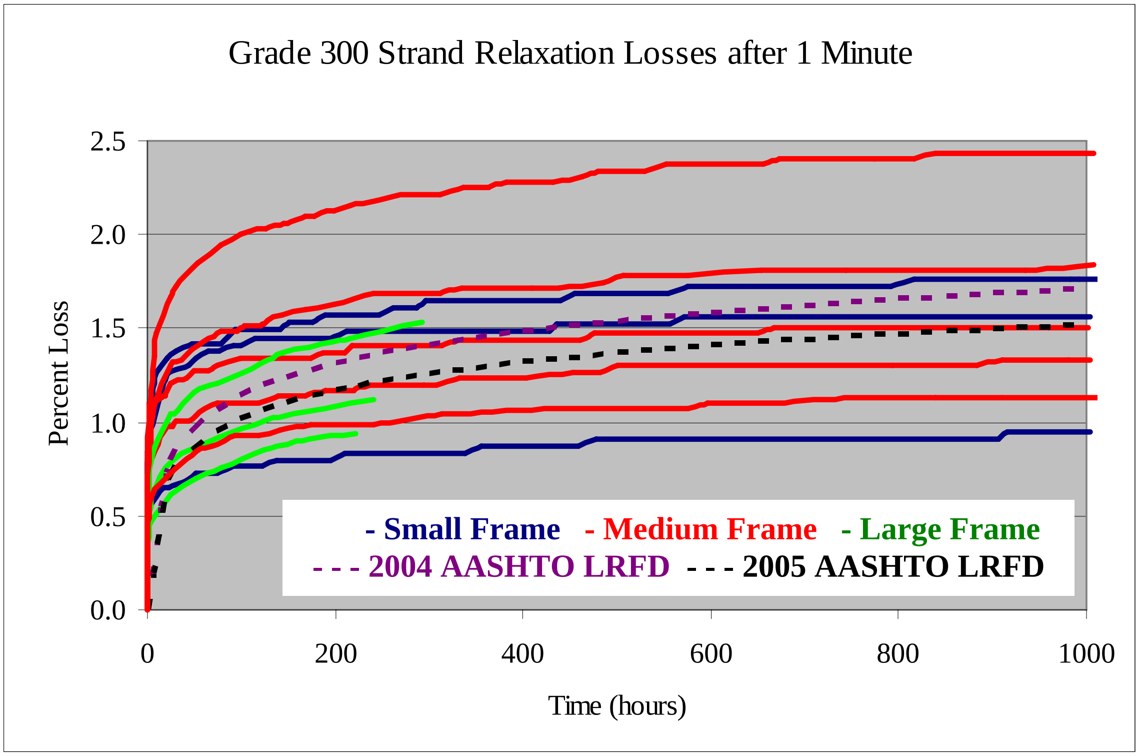

Figure 4.25: Relaxation Loss for Grade 300 Strand Measured after 1 Minute

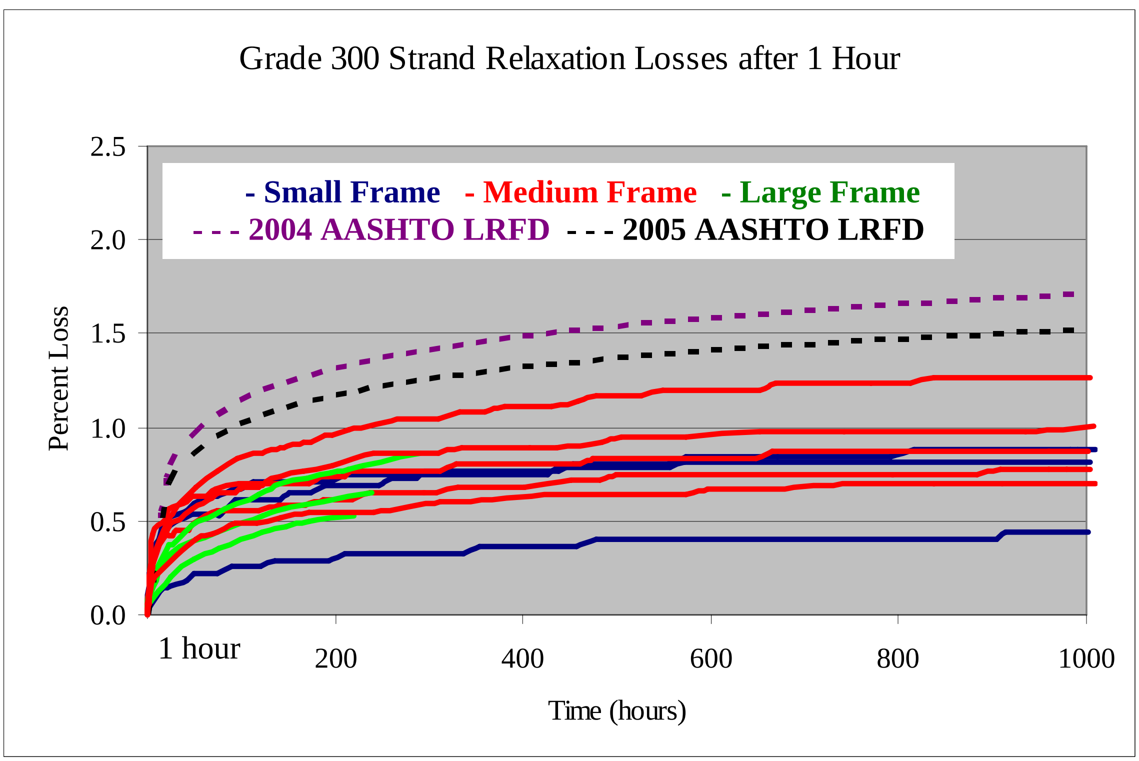

Figure 4.26: Relaxation Loss for Grade 300 Strand Measured after 1 Hour

If statistically comparing the Grade 270 and Grade 300 strands as the data was presented by assuming that no chuck slip or settlement of the frame system took place, the Grade 270 and Grade 300 strands exhibited almost identical relaxation losses. The mean losses for both the Grade 270 and Grade 300 strands, in the presentation that follows, includes every strand gripped by the magnum chucks. The mean and one standard deviation (68.26 per cent confidence interval) comparisons for the strands are listed in Table 4.17 and graphically illustrated in Figures 4.27 and 4.28.

Table 4.17: Statistical Comparison of Relaxation Losses for GR 270 and 300 Strand

Time (hours)	Grade 270 Mean Relaxation Losses (%)	Grade 300 Mean Relaxation Losses (%)	GR 270 Standard Deviation	GR 300 Standard Deviation
0	0	0	0	0
10	0.330	0.386	0.129	0.112
50	0.875	1.049	0.412	0.338
100	1.103	1.237	0.421	0.369
200	1.202	1.326	0.432	0.381
300	1.416	1.451	0.433	0.404
400	1.464	1.469	0.434	0.436
500	1.494	1.510	0.444	0.446
600	1.527	1.530	0.449	0.454
700	1.534	1.544	0.451	0.459
800	1.563	1.546	0.447	0.460
900	1.576	1.555	0.453	0.468
1000	1.586	1.565	0.452	0.462

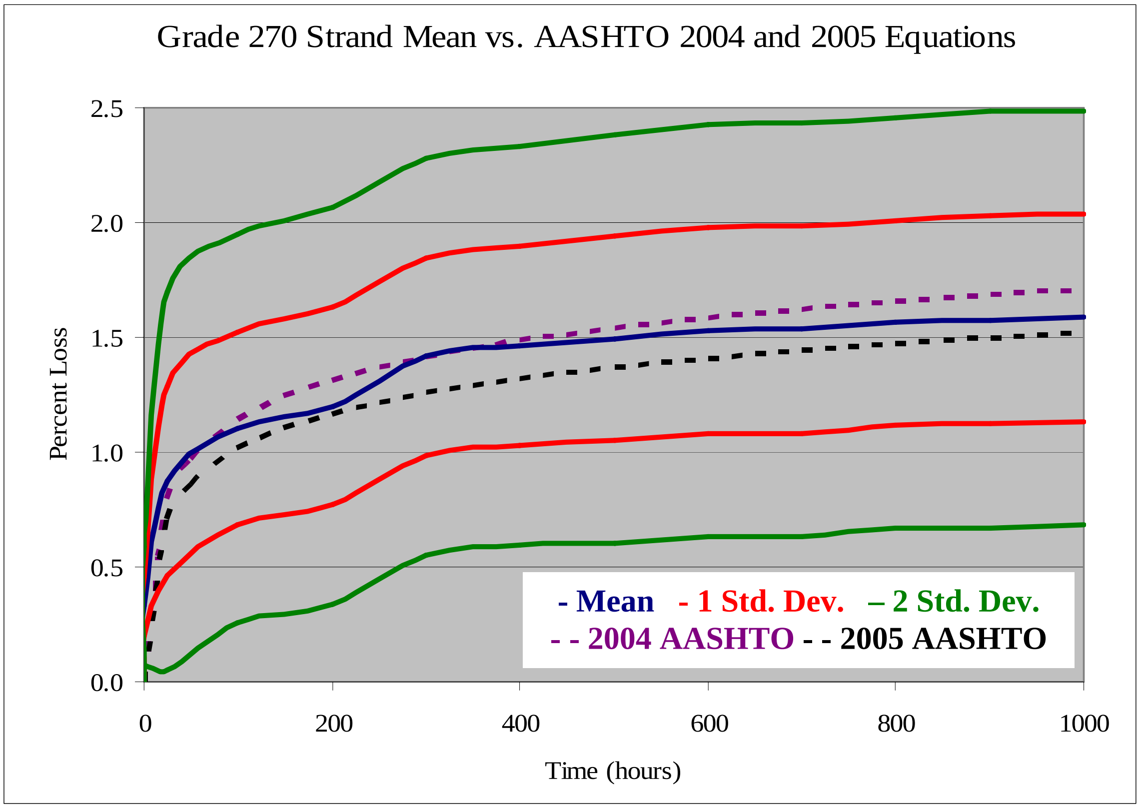

Figure 4.27: Grade 270 Strand versus AASHTO LRFD Equations

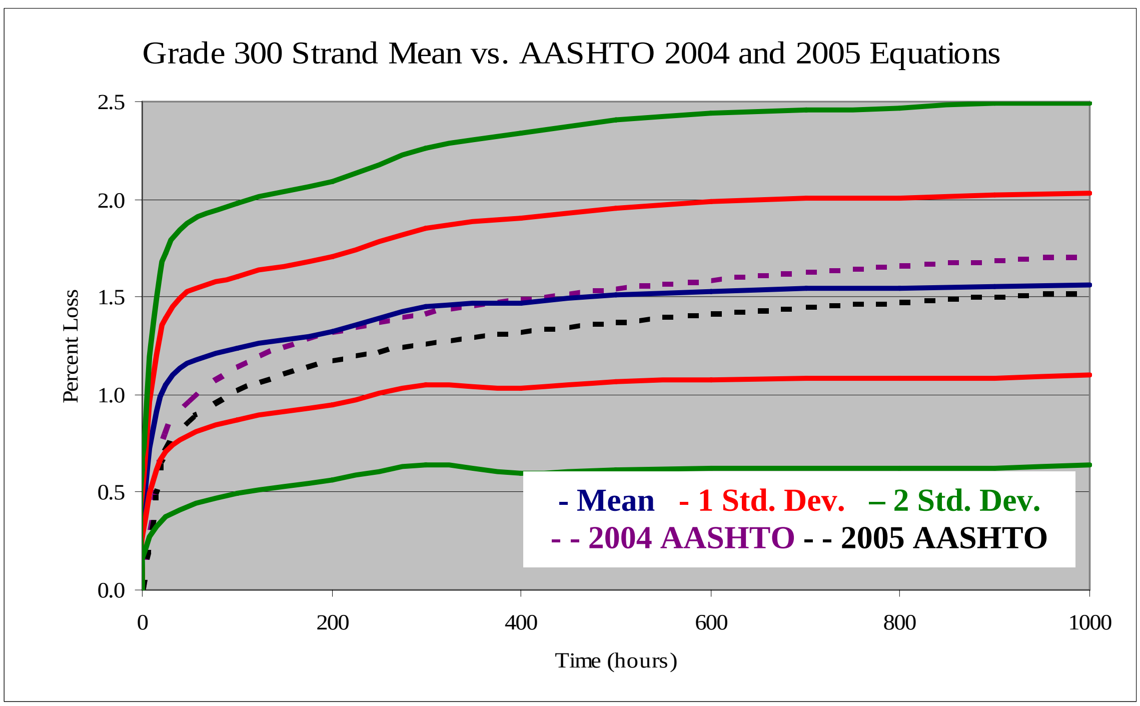

Figure 4.28: Grade 300 Strand versus AASHTO LRFD Equations

The mean losses for both grades of strand were between the 2004 and 2005 AASHTO LRFD predicted losses. Based on the statistical analysis, 95.46 per cent (two standard deviations) of every strand tested, regardless of the type, would exhibit less than 2.5 per cent losses, the ASTM A416 (2005) limit for strands tensioned between 70 and 80 per cent of their ultimate breaking stress. Perhaps of even greater importance is that based on the statistical data given, the Grade 300 strands (mean of 1.57 per cent with standard deviation of 0.45 per cent after 1,000 hours) have the same relaxation characteristics as the Grade 270 strands (mean of 1.59 per cent with standard deviation of 0.46 per cent after 1,000 hours).

While testing should be done to check the relaxation characteristics of the Grade 300 strand while embedded in concrete, the testing conducted from this research gives no indication there would be a need to change current equations based on the production of Grade 300 strand. Especially since at the 200 hour mark, there is a dip in the mean relaxation curves. The dip in the curves is due to the relaxation losses of the strands tested in the large test frames, which had relaxation losses lower than those in strand tested in the small and medium test frames. If the tests in the large test frames were carried out to 1,000 hours, the mean relaxation at 1,000 hours would have been slightly conservative to both AASHTO LRFD equations.

4.3: Impact of Material Properties on Bridges

The design example that follows will demonstrate the economy that using the Grade 300 and super strands can have on an AASHTO-PCI bulb-tee beam bridge. This design example was pulled from the Route 57 East Bound Lane Bridge over the Dan River in Halifax County, Virginia. Specifically, the interior girder from Span b from the

Route 57 Bridge was designed. The design presented here does not reflect the actual design presented and finalized by VDOT. The actual bridge was designed with a continuous span, whereas this design example shows the design of a simply-supported, interior girder from the four-span bridge. This span and girder did not control the actual design of the bridge; therefore, it is not reflected in the actual plans.

4.3.1: Introduction to Girder Design

Prior to laying out the results of the designs, assumptions made in the designs must be presented. This bridge was designed using the AASHTO LRFD Bridge Design Specification, Third Edition (2004) and Interim (2005). In accordance with the actual design, the bridge was designed with no skew. The girders were assumed to have a compressive strength of 5,600 psi at transfer and 8,000 psi at 28 days. The transverse spacing of the 107 ft long girders (104 ft center of bearing to center of bearing) was 9 ft – 2 in. The strand used in the design was low-relaxation, and strands were harped at 0.4 of the span. Normal weight concrete (150 pcf) was used, and there was a 1 in. haunch between the deck and girder as wide as the top girder flange. HL-93 loading was used as the controlling load in the design. The load criteria assumed were: 20 psf for stay-in-place forms, 15 psf for future wearing surface, 20 psf for construction excesses, and 0.3 k/ft for each parapet.

Despite the different type of strand used in each design, the final girder size selected was the BT-61 girder. Using the industry standard 0.5 in. diameter, regular area, Grade 270 strand almost made the girder size jump up to a BT-69, demonstrating that strand size and type could play a role in the actual girder size. The section properties for the BT-61 girder are given in Table 4.18.

Table 4.18: PCBT-61 Girder Properties (Bayshore Concrete Products Corp., 2001)

Area of Girder	858.7	$in.^2$
Height of Girder	61	in.
Moment of Inertia	443,100	$in.^4$
Distance from Centroid to Extreme Bottom Fiber of Beam	29.92	in.
Distance from Centroid to Extreme Top Fiber of Beam	31.08	in.
Section Modulus for the Extreme Bottom Fiber	14,809	$in.^3$
Section Modulus for the Extreme Top Fiber	14,257	$in.^3$
Weight of Beam	0.899	k/ft

Maximum moment and shear were then calculated via distribution factors and by hand. For this design, the absolute maximum moment due to the HL-93 loading was approximately 1,600 ft-kips, while the maximum shear was 65.5 kips. The load combinations Strength I, Service I, Service III, and Fatigue were evaluated and considered for this design. The Strength I load combination (Equation 4.3) assumed normal vehicle use without wind effects and was used to evaluate the strength limit state of the girder. The Service I load combination (Equation 4.4) was used to check the compressive stresses in the girder at service loads. The Service III load combination (Equation 4.5) was used to check the tensile stresses in the girder in order to control cracking. The Fatigue load combination (Equation 4.6) checked the impact that dynamic live loads had on the tensile stress range in the strands. All of the load combination equations and definitions are detailed in AASHTO LRFD (2004).

$$Strength I = 1.25DC + 1.50DW + 1.75(LL + IM) \quad \textbf{(4.3)}$$

$$Service I = 1.0DC + 1.0DW + 1.0(LL + IM) \quad \textbf{(4.4)}$$

$$Service III = 1.0DC + 1.0DW + 0.8(LL + IM) \quad \textbf{(4.5)}$$

$$Fatigue = 0.75(LL + IM) \quad \textbf{(4.6)}$$

where:

DC = moment caused by structural components and nonstructural attachments (ft-kips)

DW = moment caused by wearing surface and utilities (ft-kips)

LL = moment caused by vehicular live load (ft-kips)

IM = moment caused by vehicular dynamic load (ft-kips)

4.3.2: Comparison of Different Strands in Final Design

The first step in comparing the strands and determining the number of strands needed was to estimate the amount of prestress required for the design. The number of strands is typically governed by the midspan concrete tensile stresses at the bottom fiber (Equation 4.7) from the Service III load combination. This stress of 3.74 ksi was unaffected by the type of strand used since the same size girder was used in each design.

$$f_b = \frac{M_g + M_s}{S_b} + \frac{M_b + M_{ws} + M_{LT} + M_{LL}}{S_{bc}} \quad \textbf{(4.7)}$$

where:

f_b = bottom tensile stress (ksi)

M_g = beam self-weight moment (in.-kips)

M_s = slab and haunch weights moment (in.-kips)

S_b = non-composite beam section modulus for bottom fiber (in.^{3})

M_b = barrier weight moment (in.-kips)

M_{ws} = future wearing surface moment (in.-kips)

M_{LT} = truck load bending moment (in.-kips)

M_{LL} = lane load bending moment (in.-kips)

S_{bc} = composite section modulus for bottom fiber (in.^{3})

The precompressive stress, or stress caused by the prestressing strands acting on the concrete girder, required at the bottom of the beam is the difference between the stress from the applied loads from Equation 4.3 and the concrete tensile limit from AASHTO LRFD Article 5.9.4.2b (2004) of 0.19 times the square root of the girder's 28-day concrete compressive strength (0.54 ksi). This value was also unchanged since the girder concrete compressive strength was the same in every design. This left the amount of precompression required for an interior girder to be 3.2 ksi. Initially, the strands were assumed to be straight, and the number of required strands was determined after assuming an initial prestressing force loss of 25 per cent. Using the AASHTO LRFD (Interim 2005) to calculate losses, the original 25 per cent estimation of losses is refined, and the number of strands is altered to reflect the actual losses. The actual loss percentages in each design are shown in the overall strand comparison in Table 4.19.

After the number of strands was selected for each design, the stress limits were checked at transfer and service loads in accordance with AASHTO LRFD 5.9.4 (2004). The compression limit at transfer was 0.6 times the concrete compression strength at release (3.36 ksi). The tension limit at transfer was the minimum of 0.2 ksi and 0.0948 times the square root of the concrete compressive strength at release (0.2 ksi controlled). For service loads, the limiting stresses were based on the Service I load combination. The compression limits for permanent loads on the beam and deck were 0.45 times their respective concrete compressive strengths (3.60 and 1.80 ksi, respectively). The compression limits for permanent and transient loads on the beam and deck were 0.4 times their respective concrete compressive strengths (3.20 and 1.60 ksi, respectively). Finally, the tension limit at service loads was 0.19 times the square root of the girder concrete compressive strength (0.537 ksi). Regardless of the type of strand used, strands were harped in order to satisfy the above stress limits at transfer and service loads. The number of harped strands in each design is shown in Table 4.19.

Flexural strength was also examined in each design. The total ultimate bending moment in each design for Strength I was 8200 ft-kips. The requirements for strength were satisfied in each design. Differences in design strength existed, however, since the strength of a girder is dependent on the total area of prestressing strand and the average stress in the prestressing steel (which is dependent on the ultimate breaking strength of the strand). The design strengths for each design are shown in Table 4.19.

Table 4.19: Design Comparisons with Different Strands

Final Girder Size	Strand	Strand Diameter (in.)	Strand Area (in.^{2})	Total # of Strands	Total Area (in.^{2})	% Loss	# of Harped Strands	ϕMn (ft-k)
BT-61 858.7 in^2	GR 270	0.5	0.153	44	6.7	19.2	8	9290
BT-61 858.7 in^2	GR 300	0.5	0.153	40	6.1	17.3	6	9320
BT-61 858.7 in^2	GR 270	0.5	0.167	42	7.0	19.7	6	9630
BT-61 858.7 in^2	GR 300	0.5	0.167	36	6.0	17.1	6	9200
BT-61 858.7 in^2	GR 270	0.6	0.217	34	7.4	17.3	6	9590
BT-61 858.7 in^2	GR 300	0.6	0.217	28	6.1	17.4	6	9400

Comparisons of the savings of the Grade 300 over the Grade 270 strands were based on a couple of assumptions. Prestressing bed hardware would likely be different when using the Grade 300 strand instead of the Grade 270 strand. As noted throughout the thesis, magnum chucks (originally designed for the Grade 300 strand) had to be used in lieu of the standard chucks for Grade 300 strand relaxation testing. While the magnum chucks were slightly more expensive than the standard chucks, an assumption for comparing the two types of strands here is that the initial costs associated with obtaining any new prestressing bed hardware for the Grade 300 strand is minimal. Secondly, the assumption is made that the Grade 300 strand meets the standard spacing criterion of 2 in. on center between strands. The number of strands saved by using a Grade 300 over a Grade 270 strand of the same diameter and area is between four and six strands per girder. The most economical design based on the total area of strands was the Grade 300, 0.5 in. diameter, super area strands (total required area of 6.0 square in.). This design required eight less strands than the typical Grade 270, 0.5 in. diameter, regular area strands, which are largely considered to be the industry standard. The design with the least total number of strands was the girder with Grade 300, 0.6 in. diameter strands. This design required only 28 strands. In terms of number of strands, this is almost a 40 per cent reduction when compared to the industry standard Grade 270, 0.5 in. diameter, regular area strands.

In a significant project, the use of the Grade 300 strand could add up to a significant cost savings, not just in the quantity of strands but, in some cases, in the size of girder chosen.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This thesis had three objectives. The first objective was to test the material properties of the new Grade 300, low-relaxation prestressing strand. The tests verified the advertised breaking strength, yield strength, modulus of elasticity, elongation and relaxation properties of the Grade 300 strand. The second objective was to comment on the advantages that the super and Grade 300 strands can have on the design of bridges by evaluating a bridge girder design from the Route 57 Bridge over the Dan River, in Halifax County, Virginia. The third objective was to review ASTM A416 (2005), ASTM E328 (2002), and ASTM A370 (2005), and recommend changes if necessary.

5.2: General Conclusions and Recommendations

5.2.1: Mechanical Properties of the Grade 300 and Super Area Strands

As mentioned in Chapter 3, 30 tension tests were conducted to evaluate the ultimate breaking stress, yield stress, modulus of elasticity and elongation of several strands. Every strand tested met its advertised mechanical properties. Two different materials were used as cushioning material between the V-grips and the strand. The type of cushioning material played a role in some of the mechanical properties measured throughout the testing. The primary method used involved the ASTM A370 (2005) recommended technique of wrapping aluminum foil around the strand. The secondary method, published by Preston (1985), involved using aluminum tubing, aluminum oxide, and an epoxy compound to encase the strand and protect it from the teeth of the V-grips. Once gripped appropriately, the strand was placed in the hydraulic SATEC machine. A two-inch extensometer was placed at the mid-point of the strand to measure strain, and the testing commenced with the hydraulic head of the SATEC tensioning the strand between 10,000 and 100,000 psi/min.

Every strand tested met the guaranteed minimum ultimate breaking stress. The Grade 270 and Grade 300, 0.5 in. diameter, regular area strands behaved almost identically, both averaging ultimate breaking stresses about 7 per cent higher than their guaranteed minimum breaking stress. The super area strands, which could only be tested to standard using the aluminum oxide and aluminum tubing technique, both averaged ultimate breaking stresses about 12 per cent higher than their guaranteed minimum breaking stress. The Grade 270, 0.6 in. diameter strands also surpassed their minimum breaking stress by approximately 12 per cent. Of note with the 0.6 diameter strand is that while two tests were successful using aluminum foil, other tests failed prematurely. It is recommended that the 0.6 in. diameter strand be tested with the special grips only.

The yield stress was calculated by monitoring the stress in the strand at one per cent extension. This is because prestressing strand does not have the same clearly defined yield point that regular rebar does. Some of the strands yielded right at the 90 per cent of the minimum guaranteed breaking stress as required by ASTM A416 (2005). Other strands surpassed the minimum yield stress significantly, with stress values even above the minimum breaking stress. As with the breaking stress testing and results, there was a correlation between the yield stress and the type of gripping technique used. The aluminum foil methods resulted in lower yield and ultimate breaking stresses. The aluminum oxide and tubing technique resulted in higher yield and ultimate breaking stresses. From this data, it was concluded that the Grade 300 and super area strands exhibit adequate yield stress properties.

Modulus of elasticity does not have a required value listed in any ASTM standard. Recommended values change from source to source, with the AASHTO LRFD (2004) suggesting 28,500 ksi, when more precise data is unavailable. With the stress readings from the SATEC and strain readings from the extensometer, modulus of elasticity calculations were made by evaluating the slope of the stress-strain line leading up to the proportional limit. The results between different strands were similar. The average for all 30 strands was 28,900 ksi with a range from 27,100 ksi to 30,400 ksi. From this data, it can be concluded that modulus of elasticity is not an issue for the Grade 300 and super area strands.

The strand's ductility, or elongation properties, was also evaluated. ASTM A416 (2005) requires the total strand elongation to be greater than 3.5 per cent using a gage length of 24 in. With no 24 in. extensometer available, the 2 in. extensometer was used throughout the testing. An 11-13/16 extensometer was used for part of the testing, but was damaged when one of the strands gripped with aluminum foil failed prematurely. The average elongation for all of the 0.5 in. diameter strands was between 7 and 8 per cent. Elongation was much higher for strands with the special grips, which makes sense since those cases generally ended up with clear breaks. In other words, the aluminum foil wrapped strands were not able to extend as much as they could have, because the notching effect of the V-grip teeth through the aluminum foil on the strand caused one of the wires in the strand to fracture before its true breaking stress was reached. Regardless of the testing technique, the Grade 300 and super strands tested met the ASTM standards; therefore, the ductility characteristics are adequate.

5.2.2: Relaxation Properties of the Grade 300 and Super Area Strands

Twenty-six relaxation tests were conducted to evaluate the relaxation properties of the Grade 300 and super area strands. The Grade 300 and super area strands exhibited the same relaxation properties as the Grade 270 strands. In fact, the statistical analysis of the Grade 270 strands and the Grade 300 strands was almost identical. The mean percent loss for the Grade 270 strands was 1.59 per cent with a standard deviation of 0.45 per cent, compared to 1.57 per cent mean loss for the Grade 300 strands and a standard deviation of 0.46 per cent. Even when looking at two standard deviations (confidence interval of over 95 per cent) from the mean, both strands had losses below the ASTM limit of 2.5 per cent when stressed between 50 and 80 per cent of their breaking stress.

Trends noticed during the testing involved the length of the test specimen and the type of chucks used during testing. The longer test specimens exhibited lower relaxation losses than the smaller test specimens. Tests conducted with magnum chucks exhibited lower relaxation losses than tests conducted with standard chucks. In both cases, the results point to the possibility that there was a small amount of slip and settling in the frame that caused the loss of a small amount of stress in the strand. The meatier and heavier teeth of the magnum chucks and the longer test specimens provide truer relaxation losses.

5.3: Recommendation for Use in Bridge Girders

Based on the results of the mechanical property testing of the Grade 300 and super area strands, a design example using all of the different strands tested in this research was conducted. The bridge girder designed was based on a girder from the Eastbound Lane of the Route 57 Bridge over the Dan River in Halifax County, Virginia. The Grade 300, 0.5 in. diameter, regular area strands ended up saving four strands in a single girder when compared to the Grade 270 industry standard strand. Meanwhile, the Grade 300, 0.5 in. diameter, 0.167 square in. strands saved eight strands in the girder.

In both cases where the Grade 300 strand was evaluated, there were also approximately 2 per cent less losses than when the Grade 270 strand was used. In combination with the fewer strands needed, this reinforced the fact that the Grade 300 strand is a more economical choice for engineers. While eight strands may not seem significant, over an entire project this could add up to a significant savings. Furthermore, with the same number of strands as used with the Grade 270 strand, engineers using the Grade 300 strand would be able to increase the span length of a bridge and/or increase the transverse girder spacing of the bridge. This is when tremendous savings in time and money occur.

5.4: Recommended Publication Changes

5.4.1: AASHTO LRFD Recommendations

Based on the relaxation behavior of the tested strand, no changes are recommended to the losses section of the AASHTO LRFD Interim 2005. With regard to AASHTO LRFD (2004) Table 5.4.4.1-1: Properties of Prestressing Strand and Bar, it is recommended that the tensile strength and yield strength properties of the Grade 300 strand be included. Finally, it is recommended that Figure C5.4.4.2-1: Typical Stress-Strain Curve for Prestressing Steels from AASHTO LRFD (2004) be updated to include the stress-strain curve for the Grade 300 strand.

5.4.2: Recommendations to ASTM Standards

After testing multiple super area strands and 0.6 in. diameter, regular area strands with aluminum foil unsuccessfully, a recommendation to the ASTM committees for ASTM A416 (2005) and A370 (2005) is to make note of the inability to successfully test the larger area strands with aluminum foil as a cushioning agent. This note would have saved a lot of strand, the damaging of an extensometer, and considerable time in the testing conducted for this thesis. Another recommendation in reference to the grips is to point out that the true breaking strength of the strand will not be met using aluminum foil. Not a single strand failed with a clear break when tested with aluminum foil as the cushioning agent. The breaking stress capacity of the strands was reduced by the stress concentrations that developed in the teeth indentations caused by the grips.

Another recommendation for ASTM A416 (2005) is to publish the breaking strength requirements and yield strength requirements for the Grade 300 strands available on the market. With the economy that the Grade 300 strands provide, it is only a matter of time before they become widely used commodities on the market. Publishing these standards in the ASTM standards will enhance their popularity and familiarity among engineers.

In ASTM A370 (2005), there is a requirement to measure elongation using an extensometer with a gage length of not less than 24 in. With the high cost of extensometers, especially one of that gage length, it is impractical in many cases to make that kind of purchase. In this testing, using the 2 in. gage length extensometer measurements until it was removed and adding it to data from the SATEC crosshead displacement until fracture, elongation was calculated consistent with data collected from the strand manufacturer. Slip during crosshead movement generally occurred only in the first seconds of testing and did not play a role by the time the extensometer was removed. As a result, the recommendation is for an approved ASTM method that does not require the use of a 24 in. extensometer.

A final recommendation is in reference to the test gage length in the relaxation properties section of ASTM A416 (2005). The test gage length for relaxation tests is supposed to be at least 60 times the nominal diameter of the strand. Several tests were made with different test lengths. The strand tested in the small frames (about 74 strand diameters) passed the ASTM requirement of no more than 2.5 per cent relaxation after 1,000 hours. However, as noted in Chapter 4, it appeared as if there may have been some minute slip or settling of the test frame that impacted the results of the relaxation testing. The longer test frames mitigated the impact of slip and frame settlement. The recommendation of 60 times the nominal diameter of the strand is acceptable, but it is recommended to at least put a note in the ASTM standard making reference to the impact that even the smallest amount of slip can have on the smaller test gage lengths.

5.5: Recommendations for Further Research

While some of the questions regarding the Grade 300 strand have been answered, there are several other areas requiring further research. Some of the important areas requiring research are stress-corrosion, transfer length, cover and spacing requirements, and flexural strength. For the stress-corrosion, cover and spacing requirements, and flexural strength, the primary goals are to ensure that the behavior of the Grade 300 strand is similar to that of the Grade 270 strand. Unnecessary cracking can occur near the end of a bridge girder if inadequate spacing and cover requirements are met. The key question with flexural strength is if there will be a brittle failure of a lightly reinforced Grade 300 strand member. While the tension tests conducted in this testing show that the elongation properties (ductility characteristics) of the Grade 300 strand are virtually identical to those of the Grade 270 strand, flexural testing of the strand in beams may still be warranted. It is also important to ensure that there are no issues as far as transfer length. Once prestressing force is transferred from the jacking devices to the concrete, the strand swells and passes on a radial tension in the concrete around the strand. Ideally, the prestressed concrete members will be able to resist the increased force from the Grade 300 strands, as it has proven to do with the Grade 270 strands.

Questions that remain from the testing conducted for this thesis include testing the other gripping methods recommended by ASTM A370 (2005). There are a myriad of other cushioning materials recommended for use with V-grips, such as carborundum cloth, bra shims, and lead foil. Further tension testing of the super area and Grade 300 strand using some of the other cushioning materials to test their suitability in achieving a clear break of all seven wires of the strand is recommended. Comparisons between the behavior of the 0.6 in. diameter, Grade 300 and Grade 270 strands is another possibility. The 0.6 in. diameter, Grade 300 strand was unavailable during the testing conducted for this thesis.

A further study into the relaxation losses of strand may also be warranted. While the relaxations of the Grade 300 and super strands were almost identical to those of the Grade 270 strands, the AASHTO Interim LRFD (2005) equation for estimating losses for strand are interdependent with shrinkage and creep. Monitoring losses in prestressed concrete girders using Grade 300 strand is recommended.

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VITA

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Commissioned as a Second Lieutenant upon graduation, Aaron's first assignment was as a combat engineer platoon leader within the 1st Cavalry Division. After three years at Fort Hood which included time as a Battalion S-4 (Logistician), Company Executive Officer, and deployments to both Croatia and Bosnia-Herzegovina, Aaron attended the Captain's Career Course in Fort Leonard Wood, MO from 2000 to 2001. During his time there, he also continued his studies at the University of Missouri-Rolla, where he earned a Master of Science degree in Engineering Management.

Aaron was then promoted to Captain and assigned to Fort Belvoir, VA. After a stint as the Garrison Plans Officer, he served for over two years as the Company Commander for the MDW Engineer Company (Confined Space, Collapsed Structure, Vertical, and Deep Tunnel Rescue). Aaron then accepted a position as an instructor within the C&ME Department at West Point, NY. In preparation for that assignment, he completed studies at Virginia Tech from 2004 to 2006, where he received a Master of Science degree in Civil Engineering.

Aaron is married to the former Diana Lynn Miner and has three children, Aaron III, Alyssa, and Amaya.