Post-Tensioning and Anchorage Systems

By Geoff Madrazo*
Georgia Institute of Technology
REU at Lehigh University

Graduate Mentor: David Roke
Faculty Advisors: Dr. Richard Sause* and Dr. James Ricles*

Table of Contents

1.0 Abstract

This project was designed to acquire data regarding the behaviors of a post-tension strand and anchorage system. Failure in the strand is caused by the wedges making a notch in one or more of the wires, therefore inducing the strand the break at high loads. The use of post-tensioning in real-world applications is limited by this failure, so knowing the specific behaviors of the system is valuable for testing and research that involve post-tensioning.

Numerous stress tests demonstrated the strength of the three-part wedge under heavy loading, as well as the strand and anchor system’s ability to exceed yielding. Referencing this information for future testing will help researchers understand the properties of the PT strand and anchors, and will hopefully promote exploiting the advantages of post-tensioning.

2.0 Introduction

2.1 What is Prestressing?

Prestressing is a method of reinforcing different kinds of structural elements. It was based off of the use of rebar in concrete as reinforcement, with the main distinction being that an induced stress changes the properties of the concrete (PTI). In most applications, prestressing is used to overcome a materials’ weak tensile strength. A highly tensile steel strand or rod passes through the material, is pulled into tension and anchored on both ends to couple their properties. This prestressing applies a compressive stress on the material, which offsets the tensile stress the material might face under loading (Figure 2.1). A technique of prestressing is called post-tensioning, commonly used in concrete structures, in which the tension is applied after the material is in its final state, such as a concrete slab or a complete structure.

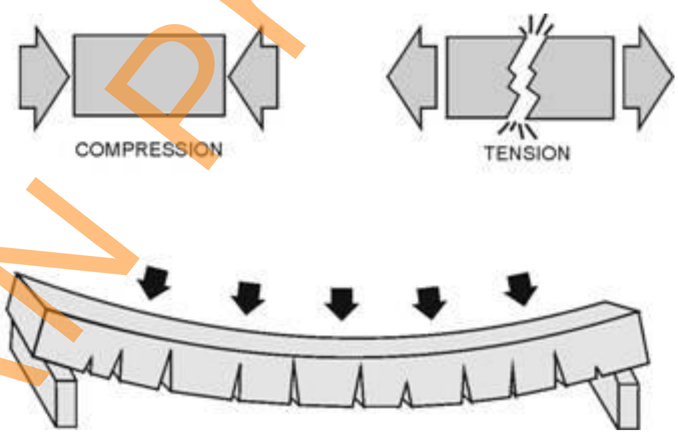

Figure 2.1 Concrete under loading
Source: PTI

Post-tensioning has been in practice since the early 20th century, but only recently have companies really taken advantage of its structural and financial benefits. For example, to a stronger concrete slab means you can build with less concrete but still retain the same structural properties as a much larger slab without post-tensioning. Less concrete means it will be less costly to manufacture, lighter to ship, and easier to install. It also allows for new designs to take advantage of a lighter concrete slab without compromising its strength.

The method of prestressing has been implemented for several decades in all types of bridges, many kinds of elevated slabs (i.e. residential and high-rise structures, parking garages, etc.), as well as foundations, walls and columns (Figure 2.2). Post-tensioning has driven the potential for longer bridge spans, larger structures, unique constructions, and more structurally sound buildings (PTI).   And because of its "rubber band-like" properties, which are very tolerant to lateral loads, prestressed members have long been used in seismic resistant structures (DSI).

Figure 2.2 Post-tensioning on a highway overpass
Source: Charlie La Barbera

2.2 Purpose

The purpose of this project is to obtain useful data on the strength and behaviors of the post-tension strand and anchor system. A reliable data set will be a valuable reference for future projects which implement post-tensioning.

2.3 Objectives

The first objective of my project is to perform multiple stress tests on the post-tension strand and anchor system. I will collect different forms of data, such as the breaking strength (T_{exp}), elongation ($\varepsilon_{max,est}$), and time (t) and analyze the sets of information. By plotting different manipulations of the data, I will observe and exploit certain trends and findings.

Dr. Maria Garlock researched Seismic Resistant Post-Tensioned Steel Moment-Resisting Frames as her Ph.D. study, which included post-tensioning running along the steel beams of a structure. Under certain loads, she observed the strand breaking near the anchors, but documented "the fracture was a ductile fracture and not caused by a notch or "bite" produced by the wedge" (Garlock). Part of the data collection from the stress tests will be to observe and understand the behaviors of the anchorage system. By carefully watching and photographing the seating and post-break states of the wedges, we should be able to see how the anchorage reacts to breaking loads.

Testing and analyzing the post-tension strand and anchor system will give me an understanding of the kind of loads and conditions it can withstand. From there I will be able to determine the right conditions and usage for the system and find a practical scope for using it.

3.0 Methods and Materials

3.1 Post-Tension Strand

Post-tension (PT) strands are manufactured in accordance to the standard American Society for Testing and Materials (ASTM) A416. It is composed of seven treated carbon steel wires, six of which are arranged in a helical pattern around a slightly larger center wire (Figure 3.1). PT strand is available in several diameters ranging from .250 in. to .600 in. For most post-tensioning applications, the standard size strand is either the .500 in. or .600 in. diameter (ASTM). Breaking strength requirements and yield strength requirements are shown in Table 3.1.

Strand Diameter (in.)	.500	.600
Min. Breaking Strength, T_U (kips)	41.3	58.6
Steel Area (in^2)	.153	.217
Strand Weight (lb/ft)	.520	.740
Min. Yield Strength, 1% Elongation, T_Y (kips)	37.17	52.74

Table 3.1 ASTM A416 requirements

Source: ASTM

3.2 Anchors and Wedges

Anchorages and wedges are manufactured in different ways for different applications. They follow the American Concrete Institute (ACI) code 318, which fundamentally states that the anchorage system is guaranteed up to 95% of the breaking strength of the strand (T_U) (ACI). For projects that require higher tensile strengths, there are various kinds of multi-strand anchors which can accommodate from two to 156 strands (Figure 3.2) (DSI). The largest anchors are mainly used in cable stayed bridges to hold up the roadway, while the smaller anchors are used in more common applications such as a highway overpass or a parking garage. For our testing we used monostrand anchorages so we wouldn't be dealing with immense amounts of released energy while breaking the strand (Figure 3.3). Wedges sit in the anchor and grip onto the strand to hold it in place (Figure 3.4). They are manufactured in two- and three- parts, both of which we tested.

Figure 3.2 Multi-strand anchor
Source: DSI

Figure 3.3 Monostrand anchor
Source: DSI

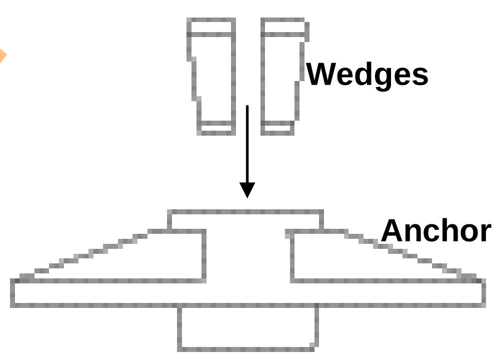

Figure 3.4 Wedges insert into anchor
Source: DSI

3.3 Testing

The first set of testing we performed were static (monotonic) stress tests on an analog universal testing machine at Fritz lab. These initial tests were performed with strand and anchors leftover from previous testing at the Advanced Technology for Large Structural Systems (ATLSS) lab. The materials were not outdated, yet their condition was somewhat in question which is why we tried to make a clear distinction for these tests in our data. Before we could begin any kind of testing, we made sure that the proper safety precautions were taken. When taking the strand to its breaking strength, there is the risk of the wedges popping out of the anchor. To account for that we put a cover over the ends to control any pieces that came loose (Figure 3.6).

The basic setup for the testing was a five foot segment of PT strand that was anchored on both of the crossheads of the universal testing machine at Fritz lab (Figure 3.5). The wedges were hand-set to be as level as possible before adding tension to the strand. After covering up the anchors to contain any flying debris, we added some tension to seat the wedges into the anchors. We tried to achieve a four to six minute elongation period (between 10 and 15 kips/min load rate), but for these tests we could only rely on knobs to fine tune the crosshead displacement and a stopwatch to monitor the time. The strands were loaded until at least one of the wires ruptured, and at that point the breaking strength and time were recorded. That process was repeated for several trials.

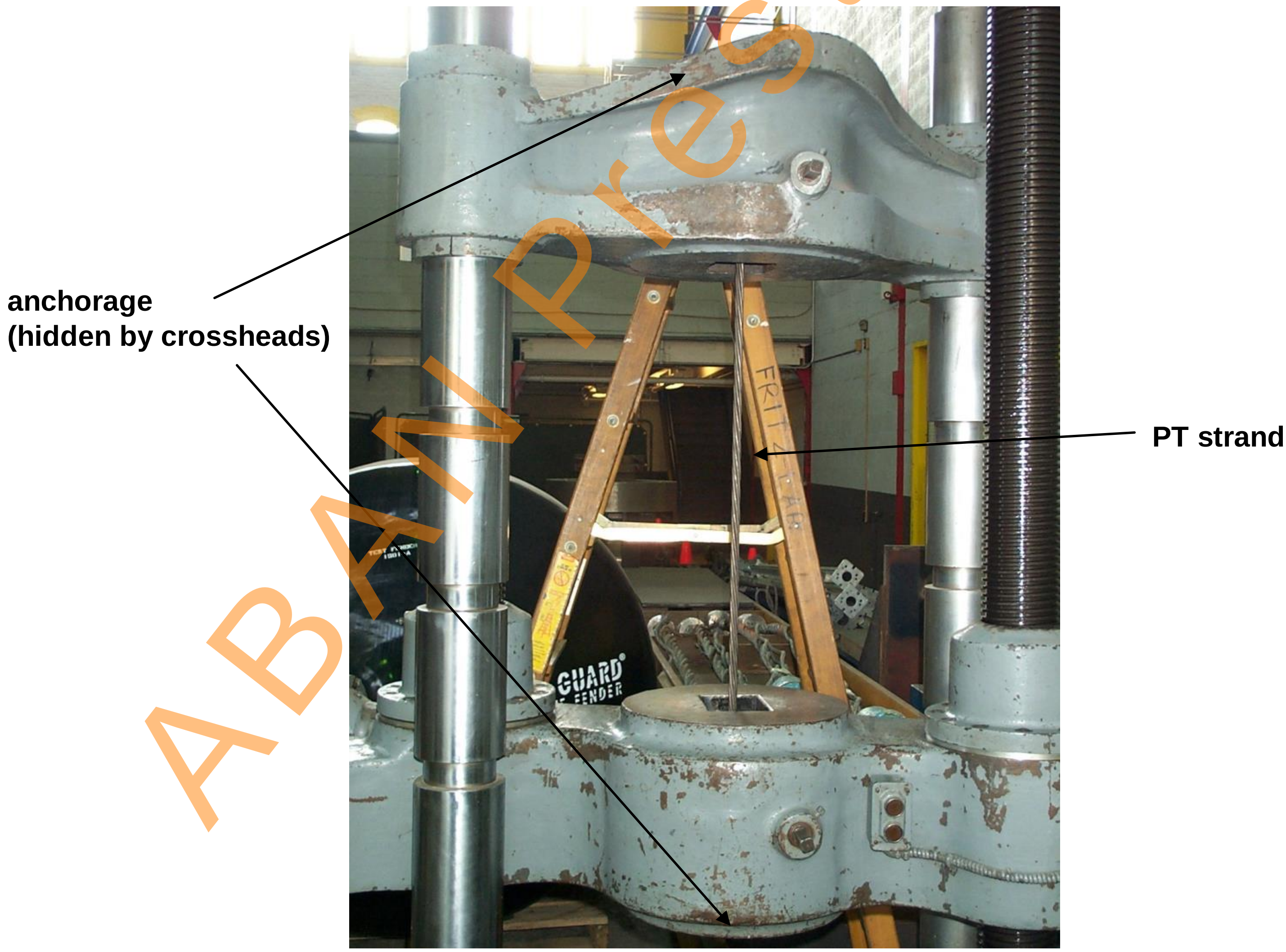

Figure 3.5 Universal Testing Machine setup at Fritz

The next phase of testing was completed with new strand, anchors and wedges provided by Dywidag-Systems International (DSI). Testing began at Fritz lab with the same procedure as before, but we ended up moving our testing to the SATEC universal testing machine in the ATLSS lab. The SATEC machine can be more controlled by a computer, and it also records data straight from the machine. Stress, head displacement, and time were the parameters that we monitored during our testing. To ensure the wedges set properly a “soft zone” was implemented, in which the crossheads displaced at a rate of .1 in/min until there was 100 lbs. tension in the strand. After the “soft zone,” we programmed the machine to load the strand at a rate of 12.00 kips/min for the first three tests, and 9.00 kips/min for the next three tests. As an added safety precaution, there was also a break detection mechanism which would stop the machine if there was a drop of at least 10% of the load past the 5000 lb. stress level. The tests were physically set up the same way as in Fritz lab (Figure 3.6).

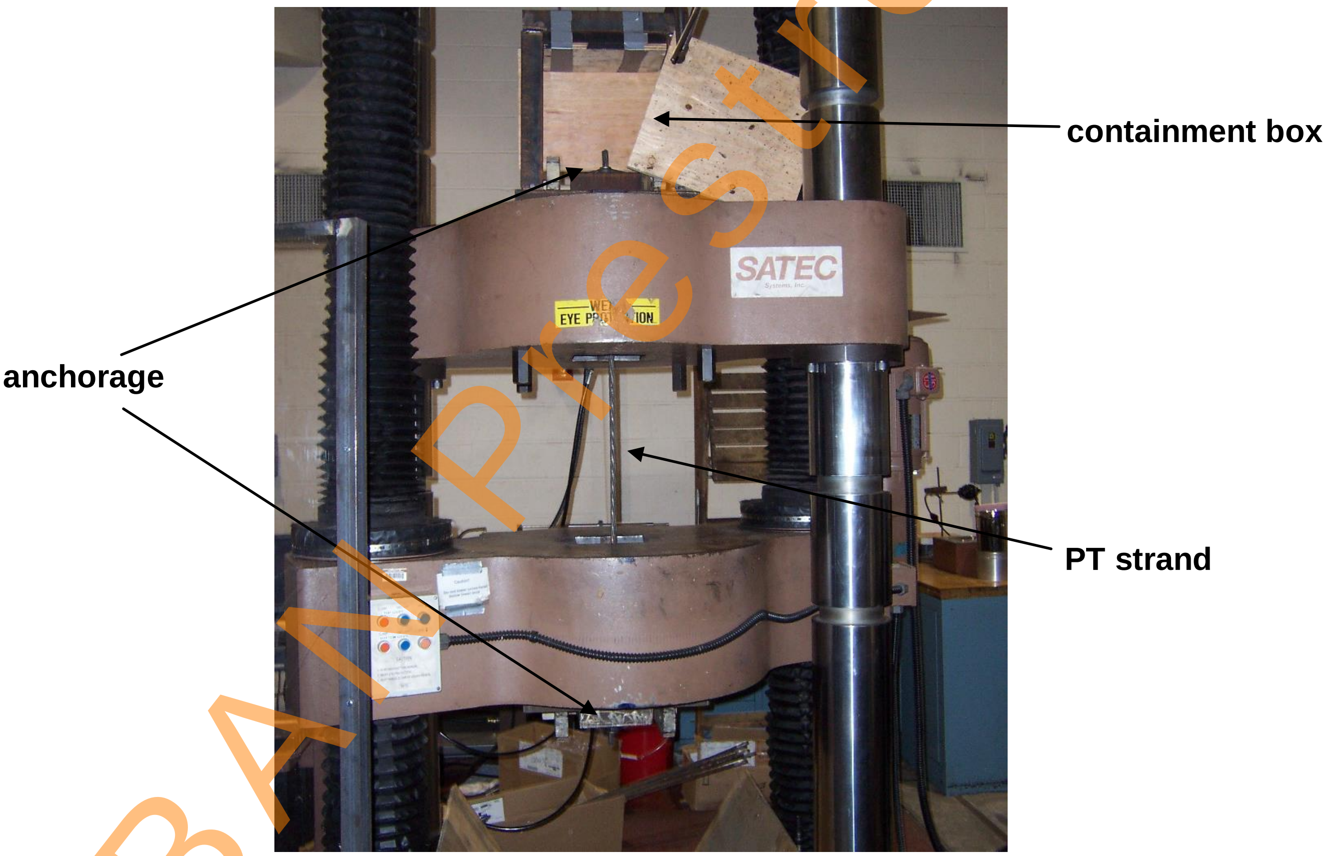

Figure 3.6 SATEC machine setup

To perform proper tensile tests to obtain a stress-strain curve of the strand, we had to find a new way of anchoring the ends. The conventional anchor-wedge system is only guaranteed to 95% T_U, so we would be missing a very important part of the curve using that system. As an attempt to solve this problem, we turned to a cold-socketing compound called Wirelock. This material is composed of a liquid resin and a granular compound (Millfield). When mixed and poured into the socket around a wire, the two components quickly form a solid resin that is greatly resistant to

compressive forces (Figure 3.7). The key to getting correct results from the Wirelock is the preparation of the strand or wire that you are bonding to. The resin is primarily used on wire ropes, which are made up of many finer wires spun around each other. Splaying the wires out and unraveling them so they appear like a broom maximizes the surface area of wire for the resin to bond to and allows for a strong connection between the wire rope and the Wirelock.

Figure 3.7 Wirelock being pouring into a socket
Source: Millfield Group

As a an alternative to Wirelock, we also tried using old grips that were found at Fritz lab. A grip is composed of two copper plates about six inches long that get compressed around the wire. The compressive force comes from inserts in the crossheads of the universal testing machine that create a wedge-like effect on the plates.

4.0 Results

4.1 Static Testing

test	# of wedges	T_{exp} (kips)	$T_{exp}/T_{u,n}$	$T_{exp}/T_{u,m}$	$e_{max,est}$ (%)	elong. rate (in/s)	load rate (kips/min)
1	3	57.50	0.98				

2	2	53.85	0.92				
3	3	53.85	0.92				
4	3	56.55	0.97	0.9371	1.341	0.1833	
5	3	55.70	0.95	0.9230	1.040	0.2880	
6	3	57.80	0.99	0.9578	2.443	0.4581	
7	3	57.30	0.98	0.9495	2.002	0.3889	
8	3	57.87	0.99	0.9589	2.504		11.459
9	3	57.68	0.98	0.9558	2.339		11.772
10	3	56.65	0.97	0.9387	1.428		11.720
11	3	56.81	0.97	0.9414	1.569		8.077
12	3	56.52	0.96	0.9366	1.315		8.901
13	3	57.08	0.97	0.9459	1.810		8.850

Table 4.1 Test data

The data collected from the static tests are documented in Table 4.1. The tests 1-3 were performed at Fritz lab with old materials, tests 4-7 at Fritz lab with new materials, and tests 8-13 using new strand on the SATEC machine. The value $T_{exp}/T_{u,m}$ is the recorded breaking strength, T_{exp}, normalized with the breaking strength ($T_{u,m}$ = 60.347 kips) provided by DSI, the manufacturer of the strand. These values show us that one-third of our tests actually reached the 95% T_U mark that the anchors are guaranteed to by ACI codes.

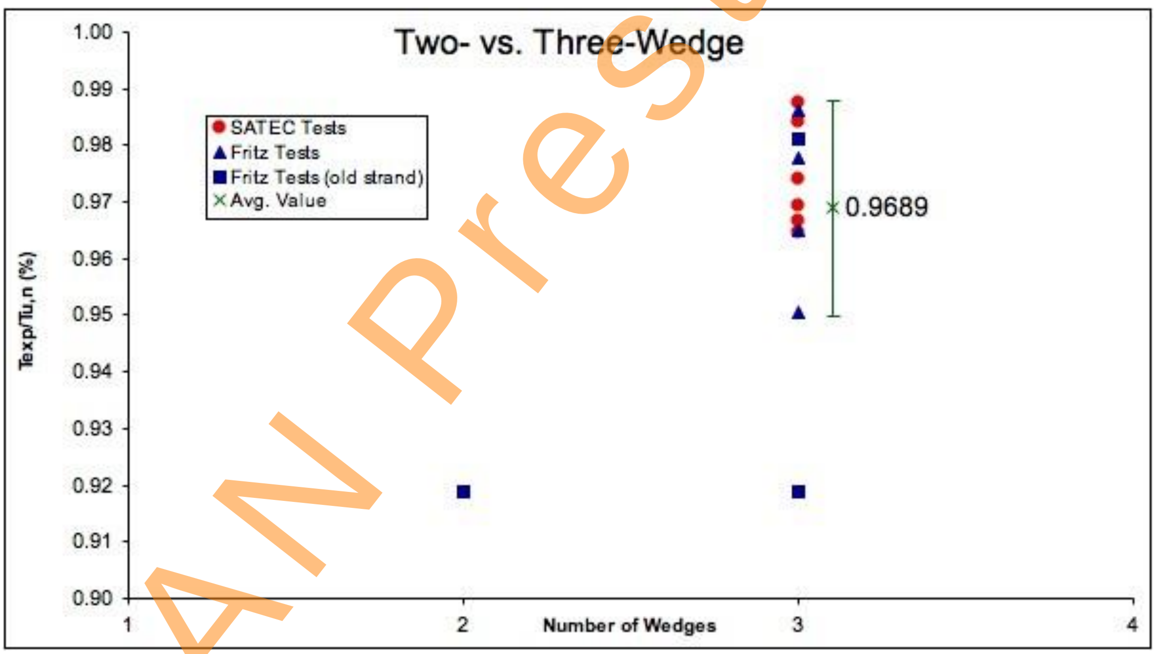

Figure 4.1 Two-part versus three-part wedges

The data in Figure 4.1 shows the difference between the breaking strength of two-part and three-part wedges. The value shown is a normalized T_{exp} with the ASTM standard minimum breaking strength 58.6 kips. This value gives a standard of comparison for the tests, and is not representative of the actual breaking strength of the strand. This figure shows a strong set of data within one standard deviation of the average and higher breaking strength for three-part wedges, but the fact that we only performed a single two-part wedge test cannot be overlooked.

The tensile tests didn't turn out as we had hoped, both ending up in the wire slipping out. The Wirelock tests slipped because there wasn't enough surface area of strand for the resin to bond to, so when taking a heavy load it started to slip (Figure 4.2). This method could still be implemented and prove successful, but we would need to expose more strand to the Wirelock for more friction. The PT strand also slipped out of the grips of the copper plates when a load was applied. We tried it several times, even pre-compressing the plates on the wire in a smaller universal testing machine. That process helped, but we still came nowhere close to the breaking strength of the wire.

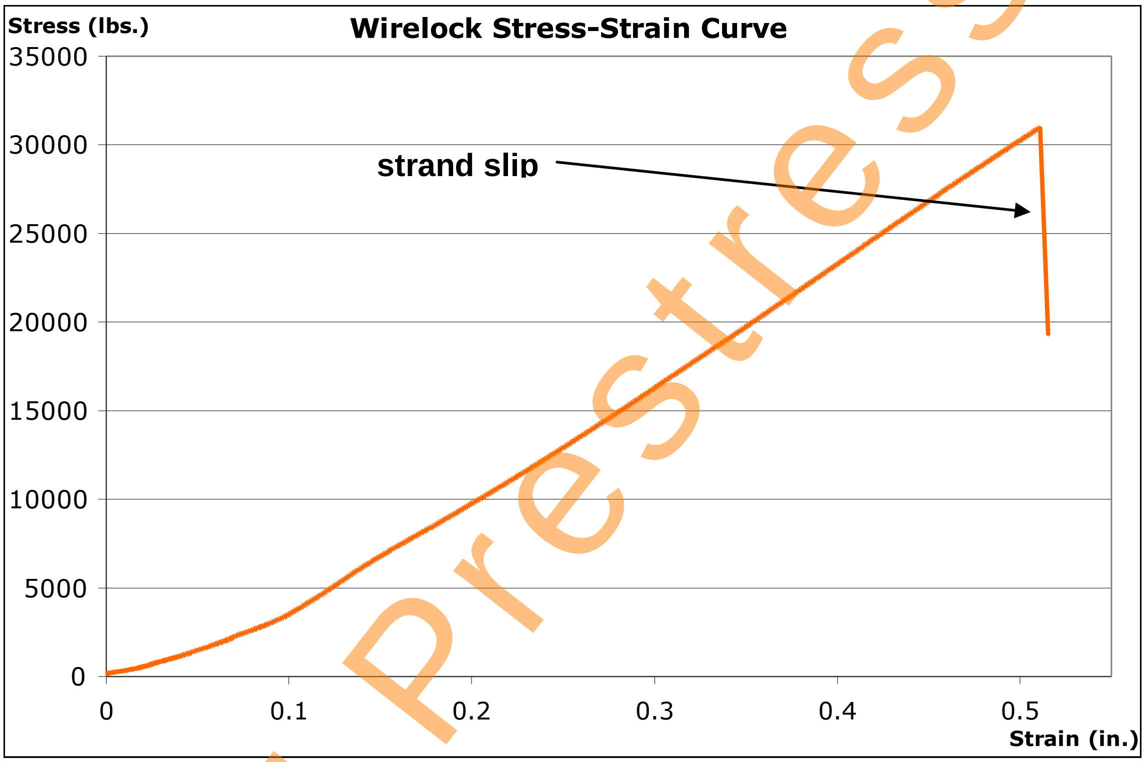

Figure 4.2 Stress-strain curve showing slipping in Wirelock

Even though we didn't get what we wanted out of the tensile tests, we were lucky enough to be able to construct a stress-strain curve of the strand with data given to us by the manufacturer. One thing about the fabricated curve is that they data given to us only goes up to around 55 kips because the strain gauges were taken off at that point. The data given to us had the ultimate breaking strength and the elongation at the break, so we were able to fill in the rest of the curve, but we have to be very aware that we didn't capture the precise behavior of the strand past the point where they took the strain gauges off. On the stress-strain curve, I also plotted the high- and low-value breaking strengths, along with the average breaking strength and the yield strength of the strand (Figure 4.3).

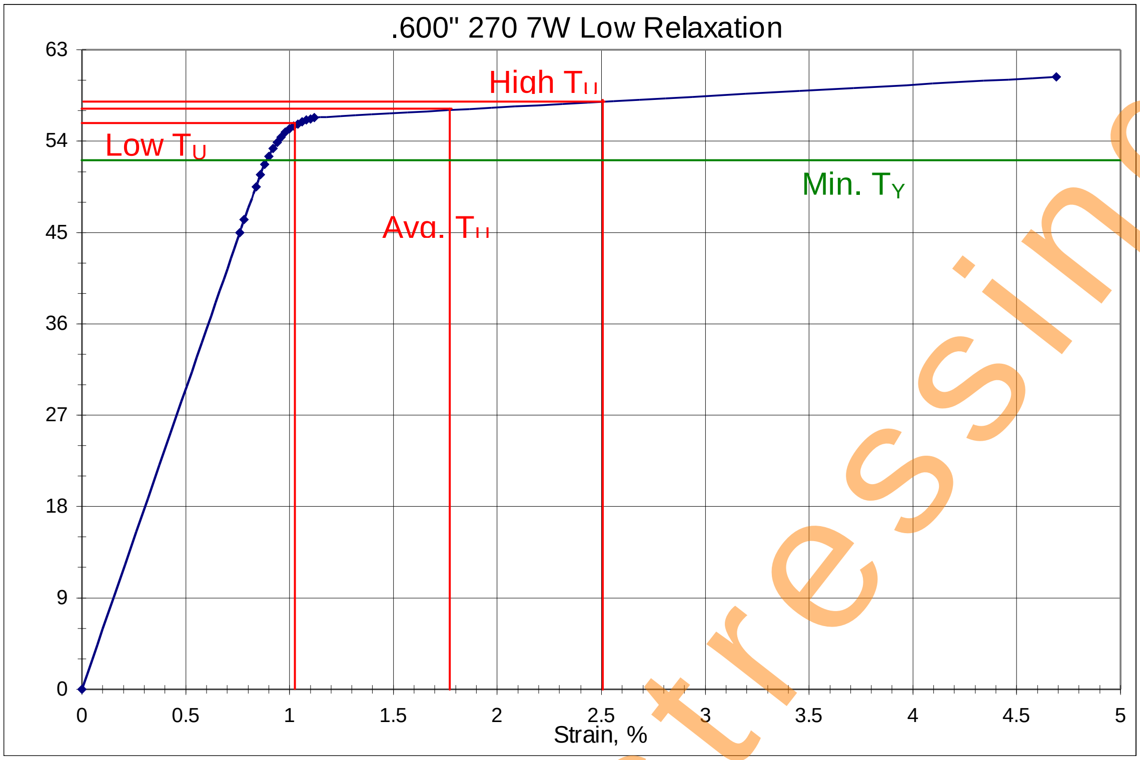

Figure 4.3 PT Strand Stress-Strain curve

5.0 Conclusions

5.1 Anchorage

Although our objectives weren't to find things wrong with the codes and standards, during our testing there was one statistic that stood out. In Table 4.1, it's very evident when you look at the $T_{exp}/T_{u,m}$ value that the anchors don't comply with ACI code 318. Only three of our tests reached 95% breaking strength of the strand, and even those hardly made it past. This finding is important to note because it is part of a building code, and those codes are supposed to be able to be achieved.

Aside from all codes, an important factor we wanted to look as was whether a two-part or a three-part wedge performed better and more reliably. In Figure 4.1, it is shown that a most of the three-wedge tests fall within one standard deviation of the average, making it a strong data set. But the fact that we only performed one two-part wedge test makes it hard to build up any points towards one or the other. We can loosely say that the three-part wedges performed better under loading than the two-part wedges, but more testing should be completed before being able to make a firm statement.

5.2 Strands

In Figure 4.3, we can see the value range of T_{exp} as compared to the yield strength, T_Y. This tells us with confidence that the strands can be taken past their yield point with the conventional anchor system. Even the lowest T_{exp} well exceeded the yield strength of the strand, making it possible to design something past the yield strength of the strand.

That design knowledge is particularly useful for the Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems projects currently being worked on by Dr. Richard Sause and Dr. James Ricles at Lehigh University. This gives them an upper limit to design to, which could mean higher prestress values, less strands used, and a better designed model from knowing these properties.

6.0 Acknowledgements

Chad Kusko
David Roke
Dr. Richard Sause
Dr. James Ricles
John Hoffner
Gene Matlock
Dr. Eric Kauffman
Lehigh University
ATLSS
NEES
NSF

7.0 References

American Concrete Institute (**ACI**), "ACI 318-05." The Structural Concrete Standard (2005).

American Society for Testing and Materials (**ASTM**), "A416/A416M-06." Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete 01.04 (2006).

Dywidag-Systems International (**DSI**), Online (2006). www.dsiamerica.com

Garlock, Dr. Maria "Design, Analysis, and Experimental Behavior of Seismic Resistant Post-Tensioned Steel Moment Resisting Frames." Lehigh University (2002).

Millfield Group, Online (2006). www.millfield-group.co.uk

Post-Tensioning Institute (**PTI**), Online (2006). www.post-tensioning.org