# FINAL REPORT

# Strand Development and Splice Device

FDOT Contract No. BD543 RPWO #19
FSU Project ID 021298

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*Submitted to:*

**Florida Department of Transportation**
Research Center
605 Suwannee Street, MS 30
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February 3, 2009

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Prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.

## SI* (MODERN METRIC) CONVERSION FACTORS

*APPROXIMATE CONVERSIONS **TO** SI UNITS*

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| | | **LENGTH** | | |
| **in** | inches | 25.4 | millimeters | mm |
| **ft** | feet | 0.305 | meters | m |
| **vd** | vards | 0.914 | meters | m |
| **mi** | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| **$in^2$** | squareinches | 645.2 | square millimeters | $mm^2$ |
| **$ft^2$** | squarefeet | 0.093 | square meters | $m^2$ |
| **$yd^2$** | square yard | 0.836 | square meters | $m^2$ |
| **ac** | acres | 0.405 | hectares | ha |
| **$mi^2$** | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| **fl oz** | fluid ounces | 29.57 | milliliters | mL |
| **gal** | gallons | 3.785 | liters | L |
| **$ft^3$** | cubic feet | 0.028 | cubic meters | $m^3$ |
| **$yd^3$** | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | | | |
| | | **MASS** | | |
| **oz** | ounces | 28.35 | grams | g |
| **lb** | pounds | 0.454 | kilograms | kg |
| **T** | short tons (2000 lb) | 0.907 | Megagrams | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| **$^oF$** | Fahrenheit | 5(F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| **fc** | foot-candles | 10.76 | lux | lx |
| **fl** | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| **lbf** | poundforce | 4.45 | newtons | N |
| **lbf/$in^2$** | poundforce per square | 6.89 | kilopascals | kPa |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

## SI* (MODERN METRIC) CONVERSION FACTORS

### *APPROXIMATE CONVERSIONS **FROM** SI UNITS*

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| **LENGTH** | | | | |
| **mm** | millimeters | 0.039 | inches | in |
| **m** | meters | 3.28 | feet | ft |
| **m** | meters | 1.09 | yards | yd |
| **km** | kilometers | 0.621 | miles | mi |
| **AREA** | | | | |
| **$mm^2$** | square millimeters | 0.0016 | square inches | $in^2$ |
| **$m^2$** | square meters | 10.764 | square feet | $ft^2$ |
| **$m^2$** | square meters | 1.195 | square yards | $yd^2$ |
| **ha** | hectares | 2.47 | acres | ac |
| **$km^2$** | square kilometers | 0.386 | square miles | $mi^2$ |
| **VOLUME** | | | | |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
| **L** | liters | 0.264 | gallons | gal |
| **$m^3$** | cubic meters | 35.314 | cubic feet | $ft^3$ |
| **$m^3$** | cubic meters | 1.307 | cubic yards | $yd^3$ |
| **MASS** | | | | |
| **g** | grams | 0.035 | ounces | oz |
| **kg** | kilograms | 2.202 | pounds | lb |
| **Mg (or "t")** | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| **TEMPERATURE (exact degrees)** | | | | |
| **$^oC$** | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| **ILLUMINATION** | | | | |
| **lx** | lux | 0.0929 | foot-candles | fc |
| **$cd/m^2$** | $candela/m^2$ | 0.2919 | foot-Lamberts | fl |
| **FORCE and PRESSURE or STRESS** | | | | |
| **N** | newtons | 0.225 | poundforce | lbf |
| **kPa** | kilopascals | 0.145 | poundforce per square inch | $lbf/in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Strand Development and Splice Device | | 5. Report Date<br>February 09<br>6. Performing Organization Code |
| 7. Author(s)<br>M. D. Roddenberry and W. Potter | | 8. Performing Organization Report No.<br>FSU Project ID 021298 |
| 9. Performing Organization Name and Address<br>FAMU-FSU College of Engineering<br>Department of Civil and Environmental Engineering<br>2525 Pottsdamer St. Rm. 129<br>Tallahassee, FL 32310-6046 | | 10. Work Unit No. (TRAIS)<br>11. Contract or Grant No.<br>BD543 RPWO #19 |
| 12. Sponsoring Agency Name and Address<br>Florida Department of Transportation<br>Research Center<br>605 Suwannee Street, MS 30<br>Tallahassee, FL 32399-0450 | | 13. Type of Report and Period Covered<br>Final Report<br>April 2007 – February 2009<br>14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract


A new device for gripping prestressing strands was developed and tested. The device could provide a means of anchoring the terminal end of a strand in order to provide a mechanism for developing bonded strand at the service limit state, to provide this mechanism at the strength limit state, and to develop unbounded strand at the strength limit state. It could also be used to mechanically splice strands together. Grouting this device into a member may reduce the development length of the strand, thereby increasing the effectiveness of the strand for reducing tensile stresses and cracking.

The prestressing strands used in all tests were unstressed and were 0.5-inch diameter, 270 ksi, low-relaxation. Preliminary tests were performed on four device lengths: 6.38 in., 7.94 in., 9.56 in., and 11.38 in. The inside diameters of the devices were either 0.79 in. or 0.94 in. Sika 300PT grout was used to bond the device to the prestressing strand. Load and displacement were measured throughout testing, and load was applied until there was no increase in force and excessive displacement had occurred. A maximum load of 22 kips was attained for the 11.38-inch device. The two shorter devices carried around 14 kips.

Further tests were performed on devices made from one-inch schedule 40 pipe with the interior roughened with a 0.75-inch pipe tap. Four device lengths were tested: 6, 9, 12, and 18 in. SS Mortar was used for the grout. Each device was cast in an 8 in. x8 in. concrete block. For all specimens, the average bond stress was an average of 1.36 ksi. The maximum load attained was for the 18-inch device, and was about 40 kips, or 97% of the ultimate strength of the strand. The 12-inch device would be the longest for practical use; this device strength was about 25.6 kips, or 62% of the ultimate strength of the strand.


| 17. Key Word | 18. Distribution Statement |
|---|---|
| Prestressed concrete, prestressing strand, strand splice | No restrictions. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified. | Unclassified. | 24 | |

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

## ACKNOWLEDGEMENTS

The authors would like to thank the Florida Department of Transportation (FDOT) for providing the funding for this research. The authors are grateful to the FDOT Structures Research Laboratory crew for their help and for performing the tests that were the basis for this study.

# EXECUTIVE SUMMARY


A new device for gripping prestressing strands was developed and tested. The device could provide a means of anchoring the terminal end of a strand in order to provide a mechanism for developing bonded strand at the service limit state, to provide this mechanism at the strength limit state, and to develop unbounded strand at the strength limit state. It could also be used to mechanically splice strands together. Grouting this device into a member may reduce the development length of the strand, thereby increasing the effectiveness of the strand for reducing tensile stresses and cracking.

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# 1.0 Introduction

## *1.1 Background*

Prestressed concrete members such as piles and beams are commonly used in bridges constructed in Florida. Prestressed members can be either precast or cast-in-place and the prestressing strands can be either pretensioned or post-tensioned. The prestressing strands, typically either 0.5 in. or 0.6 in. diameter, used in these members are critical in overcoming tensile stresses that would otherwise cause cracking in the concrete, due to internal bending or shear forces. The strands are bonded either directly to the concrete member, as in the case of pretensioning, or to ducts that are cast in or through the concrete member, as in the case of post-tensioning.

This project consists of testing a new device for gripping pretensioning strands. The device could potentially serve several purposes: 1) to provide a mechanism for developing bonded strand at the service limit state, 2) to provide this mechanism at the strength limit state, 3) to develop unbonded strand at the strength limit state, and 4) as a method for splicing strands together. Each of these mechanisms will be described below and the purpose of the device to enhance these mechanisms will be discussed in Section 1.2.

The first purpose of the device relates to the development of bonded strand at the service limit state. To appreciate the importance of this development, one must first understand the method and nature of prestressing. For example, to construct a prestressed, pretensioned beam, strands are stressed between stand-alone bulkheads, then concrete is cast around the strands and into the desired beam shape, the concrete is allowed time to cure, and the strands are cut from the bulkheads. By cutting the strands, the strand force that was once resisted by the bulkheads is imparted to the beam. The force is transmitted by friction between the strand and concrete over a distance, beginning from the end of the bonded region (a majority of the strands are typically bonded for the entire beam length). The force in the strand, therefore, varies from zero at the end of the bonded length to the effective prestressing force at some distance from the end of the strand. This distance is often called the "transfer length," which is typically assumed to be 60 strand diameters (AASHTO 2007, 5.11.4.1). For service level stresses, the reduction in force in the strand must be accounted for, particularly at the end of the beam when designing for shear and at other locations in the beam for moment.

The second purpose of the device relates to the development of bonded strand at the strength limit state. For strength design, in which the beam is checked to ensure that the ultimate moment capacity (i.e., the moment at which the materials will fail) is not exceeded when subject to factored load conditions (i.e., if the member is overloaded beyond the service level). Under these conditions, the stress in the prestressing strand increases to the "stress at nominal resistance." This requires an additional length for the build-up of this force, called the development length. Therefore, the force in the strand varies from zero at the end of the strand to the "stress at nominal resistance" over the development length. This variation in force must be accounted for in bending and shear design at the strength limit state. Furthermore, this is of particular importance near the end of the beam where large forces are concentrated from the bearing reaction. The effect of the strand force on the beam's strength and resistance to cracking can be demonstrated by a strut-and-tie approach or by the Modified Compression Field Theory.

The third purpose of the device relates to the development of unbonded strands at the strength limit state. Often, strands are debonded near the ends of the beam and at various points along the beam. The reason for doing this is that the strands are mostly needed to counteract tension in the bottom of the beam at midspan due to the beam self-weight. Beam depth and strands are chosen such that the tension in the bottom does not exceed the allowable when the beam is fully loaded with dead and live loads, but at the same time the compression in the top due to self weight and dead loads is not overcome so much by tension due to prestressing that cracking will occur. At the ends of the beam, where there is no or very little compression in the top due to self weight, prestressing forces cause too much tension and, therefore, become detrimental. Typically, straight strands are used, and they are debonded in areas where the prestressing force is not needed or where a reduced prestressing force is needed. Debonding is done by placing the strands in sleeves so the strands are not attached to the concrete. Providing a means for developing the strands to resist either overloads or all loads that are placed after the self weight, depending on when the device is installed, may "activate" the strands for strength conditions or as a posting avoidance measure. This may be particularly beneficial for retrofitting beams designed to older standards that are showing signs of distress such as web cracking at the ends.

The fourth purpose of the device may be to provide a means of splicing strands either for construction practices, retrofitting, or repair.

### *1.2 Objectives*

The objective of this project is to develop and test a device that can grip and carry the force in a prestressing strand. The device will be designed to have the capability to perform this task along with having a small footprint. As discussed in Section 1.1, potential uses for this device are to provide a means of anchoring the terminal end of a strand or a means of mechanically splicing strands together. Grouting this device into a member may reduce the development length, thereby increasing the effectiveness of the strand for reducing tensile stresses and cracking. If the strand is anchored in the device at the time of stressing, it may be beneficial for the first and second conditions discussed in Section 1.1. If the anchor is put in place after the strand is stressed, it may be beneficial for the third condition. Another potential use for the device is to mechanically splice strands together, as in the fourth condition.

Before the device is tested for any of these in-place conditions, isolated tests on the device must be completed.

## 2.0 Background and Literature Review

### *2.1 Theory of Bond in Prestressing Steel*

The bond of prestressing steel to concrete or grout is dependent on three main factors: adhesion between the steel and concrete or grout, friction between the steel and concrete or grout, and mechanical restraint. The adhesion is only present if no relative slip has taken place between the steel and concrete or grout. The frictional bond is due to the frictional resistance between steel and concrete or grout; however, in prestressing, the frictional resistance becomes more effective with the Hoyer Effect. The Hoyer Effect is due to the increase in strand diameter as the tension in the strand is released. This increase in diameter creates a radial pressure that is exerted to the surrounding concrete thus increasing the frictional resistance between the steel and concrete or grout. A depiction of the Hoyer Effect is given in Figure 1. Mechanical restraint is provided by the irregular surface of the strand, which bears against the helical impressions in the concrete as the strand moves. The performance of this mechanism is limited due to the smooth surface of the individual wires. (Janney 1954; Luthi 2005)

An important aspect of bond stress in pretensioned concrete is the transfer bond. At the release of the prestressing, the force is applied to the concrete through the transfer bond. Based on the strain differentials between the steel and concrete, slippage of the strand will occur in this transfer region, thus the adhesion mechanism can be discounted. This allows only the frictional bond and mechanical restraint to provide resistance in the transfer region. (Janney 1954; Luthi 2005)

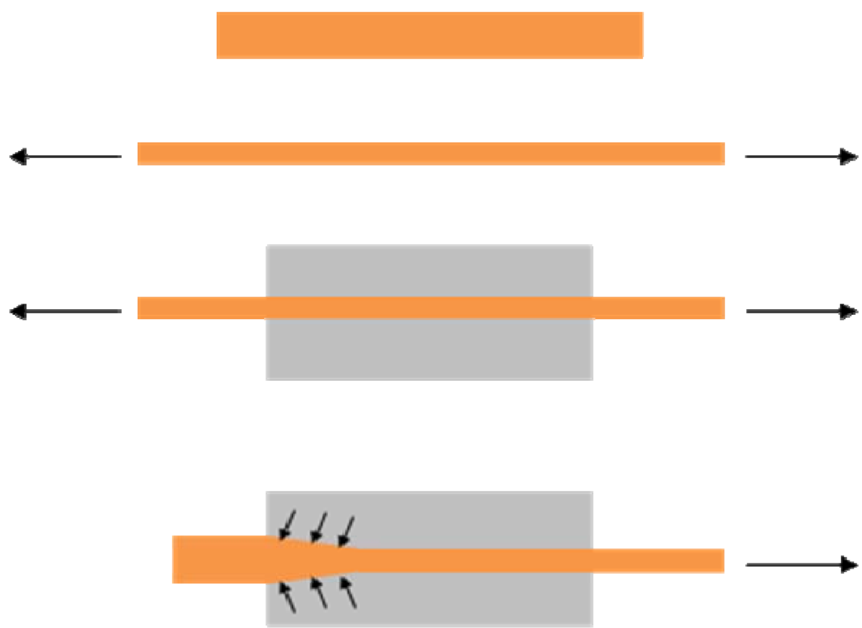

**Figure 1: Hoyer Effect**

### *2.2 Previous Research*

The research involved in the bond performance of prestressing steel has been extensive; however, the concept of using a grouted device as a terminal anchorage or splice for prestressed strand is limited. The development of a splice or anchorage for deformed mild reinforcement has been accomplished by a grouted sleeve and proves to be very effective. The deformed reinforcement, however, has a lower strength and a greater surface area with surface irregularities that allows developing the reinforcement easier. A similar approach to anchoring or splicing the strand is used in this study.

Research has been conducted that involved anchoring Carbon Fiber Reinforcing Polymer (CFRP) strands with highly expansive materials (HEM). Typical wedge anchors cannot be used to grip the CFRP due to the low shear strength and vulnerability to brittle fracture. The HEM grout creates a confining pressure between the steel device and the strand which increases the frictional bond. The HEM grout is used to anchor CFRP rods for tension tests as well as anchoring CFRP strand components in some cable-stayed bridges, i.e. Penobscot Narrows Bridge. (Rohleder 2008, Harada 2001) This product is not used in the following research because it is not a readily available product, and little research has been conducted on the long term durability and other aspects.

There has also been very little research on the use of mechanical devices for the use of anchoring strand as to improve the performance of pretensioned concrete beams. Lybas (2003) investigated several concepts of strand anchorage devices to enhance the shear strength of pretensioned concrete beams. It was discovered that devices placed externally to the beam enhanced the ultimate capacity and ductility of the beams. These devices were also deliberately located on strands with debonding between the concrete and strand near the end of the beam. Devices that were located internally or were not debonded did not perform as well. The placement of the devices allowed for a more favorable strut-and-tie failure, which requires a fully developed strand (tie). (Lybas 2003)

A similar study was also conducted by Shahawy (2001) on the *Enhancement of the Performance of Prestressed Concrete Girders Using Strand Anchorage.* A mechanical anchorage (wedge) was placed externally to beams after the strands were initially released. In order for the wedges to engage, the strand had to slip. The effect of the anchorages was similar to the study by Lybas (2003) in that there was noticeable improvement in the ultimate flexural and shears strength as well as improved ductility. Both studies demonstrate that if strand slip is eliminated or minimized then the strength of the beam can be enhanced.

## 3.0 Methodology

### *3.1 Experimental Procedures*

The tasks required for the testing involved preliminary research and design of the device(s). Once the design of the device was completed, a preliminary device was constructed. Testing was performed on a series of the preliminary devices that isolated the bond interaction between the strand and the device. Changes were then made to the device as a result of the preliminary testing, and a series of additional tests were completed. All testing was performed on unstressed prestressing strands. Load and deflection were recorded throughout testing.

*3.2 Test 1 Series – Preliminary*

Initial testing was completed on a series of devices with varying lengths to acquire an understanding on the performance of the device. Construction of the devices involved welding a series of threaded couplers together to reach the desired lengths. The lengths of devices A through D were as follows: A – 6.375 in., B – 7.9375 in., C – 9.5625 in., and D – 11.375 in. The inside diameters of the couplers were 0.788 in. for device A thru C and 0.94 in. for device D. Two each of devices A through C and one of device D were tested, for a total of seven devices. The prestressing strand used in the testing was 0.5-inch diameter, 270 ksi, low-relaxation. Sika 300PT grout was used to bond the device to the prestressing strand. The grout was placed through 0.25-inch holes machined at each end of the device. The prestressing strand was centered within the device and sealed at each end. The device and prestressing strand were then set at a slight angle with the grout injected into the low point until consistent flow was obtained from the high point. The anchors are shown in Figures 2 and 3.

The testing involved using a hollow-core hydraulic actuator, with a hand pump, to apply a force to the device casing. The strand was centered within the actuator and anchored on one end with the typical strand anchor and on the other end with the device. The displacements of the device and applied load were recorded during testing. The load was applied until no increase in force and excessive displacement (2 or 3 in.) had occurred. Figure 4 shows the test setup. During testing, the device had a tendency to twist, and on some tests wrenches were used to restrain the device. Grout cubes were made at the time of casting and tested for compressive strength several months after testing due to the inaccessibility of the universal testing machine. The compressive strength of the grout for the Test 1 Series, 300 PT Grout, was 4.8 ksi.

**Figure 2: Anchor Device - Test 1 Series**

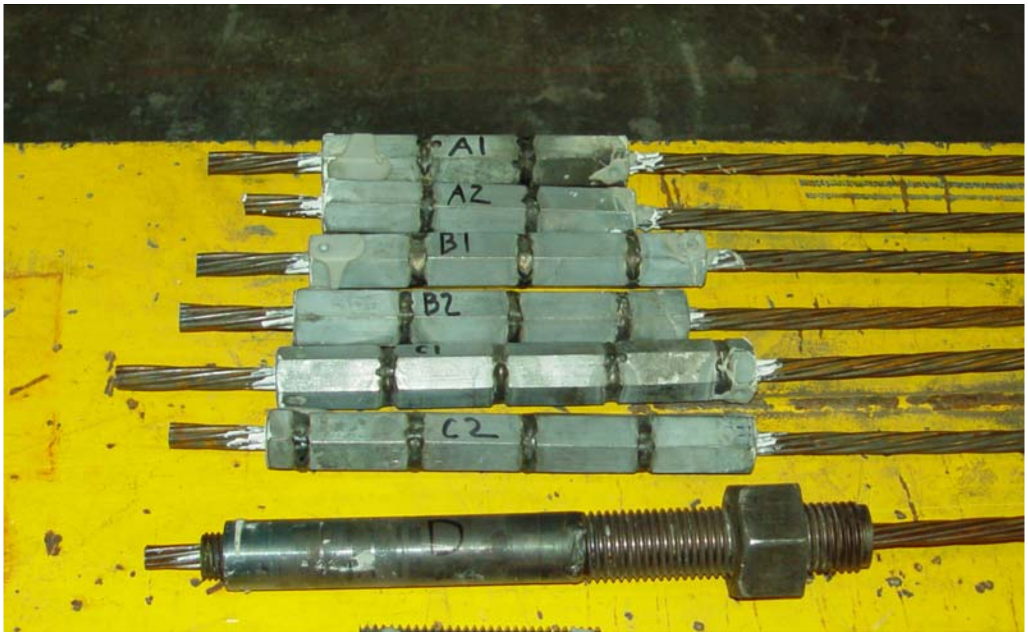


**Figure 3: Anchor Device after Grouting - Test 1 Series**

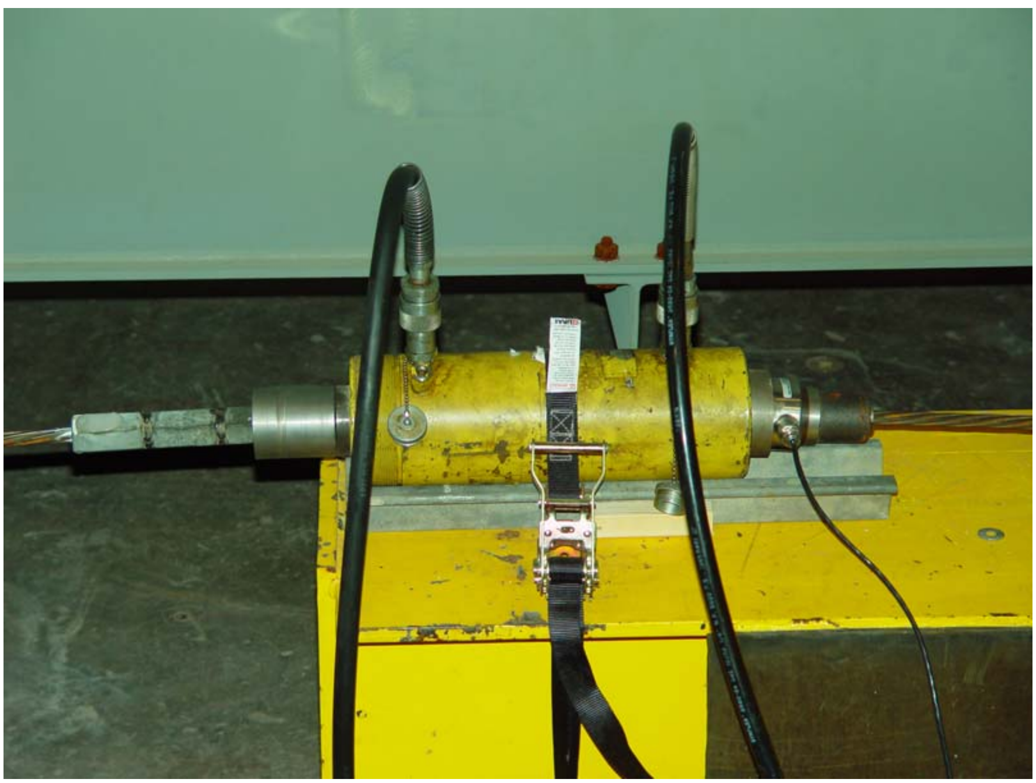

**Figure 4:  Test Setup - Test 1 Series**

### *3.3 Test 2 Series*

Test 2 Series incorporated the device modifications based on findings from the Test 1 Series. The device was constructed using one-inch schedule 40 pipe with the interior of the pipe roughened with a 0.75-inch pipe tap. Four device lengths were constructed, 6, 9, 12, and 18 in., with three devices per each length, totaling 12 devices. The inside diameter of the pipes was 1.0625 in. The same prestressing strand diameter and type as in Test 1 were used. SS Mortar was used as the grout, which is more commonly used in a reinforcing bar splice device. The SS Mortar is believed to achieve a higher bond stress based on the greater compressive strength. The placement of the grout involved orienting the device vertically and sealing one end. The grout was poured into the device with the strand centered and rodded with a wire as to prevent entrapped air pockets. Figure 5 shows the casting setup. Once the grout hardened, the device was placed in formwork, and concrete, 3000 psi mix, was cast around the device. The concrete was used as a restraint to prevent the device from twisting during the test. The dimensions of the concrete block were 8 in. x 8 in. x device length. Figure 6 shows the devices encased by the concrete.

The test setup was similar to that of the Test 1 Series with minor modifications. A hollow-core actuator, with a hand pump, was used to apply the force to the device and concrete block. To test for the bond of the strand to the device, a steel insert was placed so that the force would be applied to both the device and concrete block. This prevented the device from pulling out of the concrete block. Adjustable steel plates were used on either side of the concrete block to prevent twisting during loading. Three displacement gages were monitored during testing, with two gages on the active end and one on the dead end. The dead end displacement gage monitored only the slip of the strand, while the other two gages monitored the slip along with elastic displacement of the strand due to the applied force. Figure 7 shows the test setup. Grout cubes were tested for compressive strength after the completion of testing. The Test 2 Series, SS Mortar, grout had a compressive strength of 11.1 ksi.

**Figure 5: Casting of Device - Test 2 Series**


**Figure 6: Device Encased in Concrete**

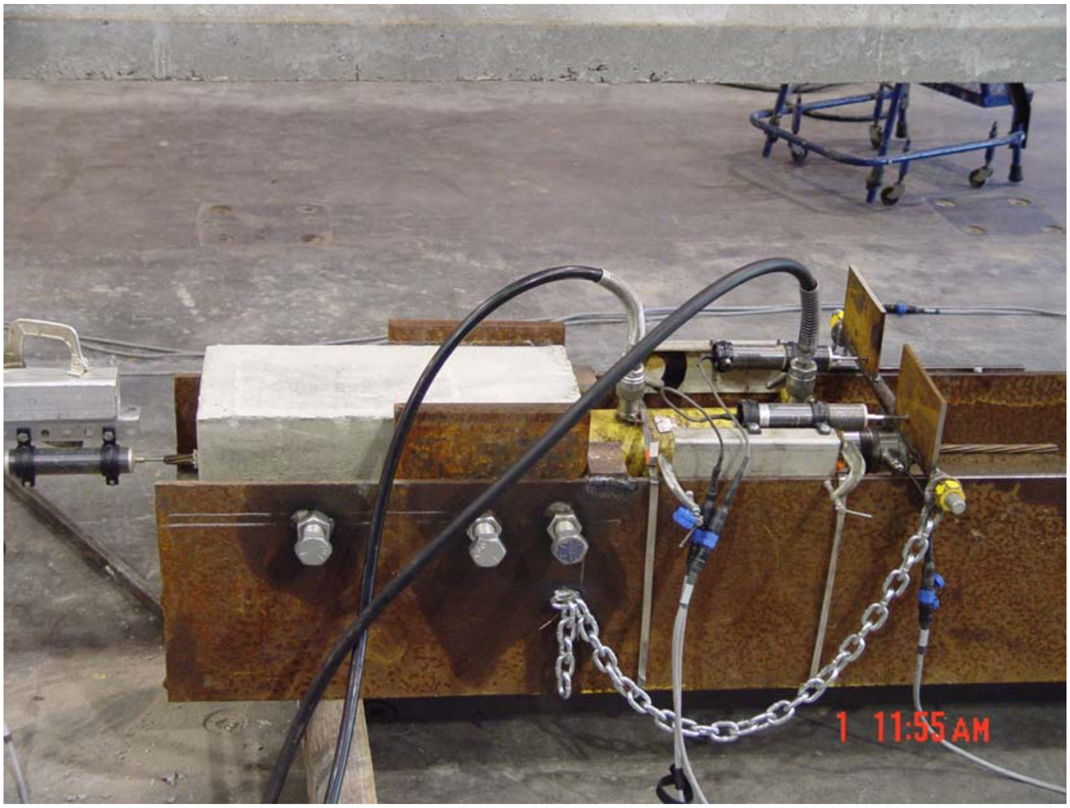


**Figure 7: Test 2 Setup**

## 4.0 Test Results and Discussion

### *4.1 Summary of Data*

The results for the Test 1 Series of devices were inconsistent for the maximum load achieved at initial slip of the strand. Figure 8 is a plot of the load versus displacement for the Test 1 Series. Device D had the highest load at initial slip, approximately 16 kips, with a maximum load of 22 kips. Device C2 reached 14 kips before strand slip and maintained a maximum load of 19 kips. The capacity of device C1, which had the same nominal dimensions as C2, occurred earlier at around 8 kips and with a drop in load as slip initiated. Further investigation of device C1 indicated that the bond between the grout and the strand was not sufficient due to voids in the grout. Devices A2, B1, and B2 performed similarly with the load at slip being between 10 and 11 kips and a sustained load around 14 kips. Device A1 is not shown in the graph due to an improper installation of the displacement gage.

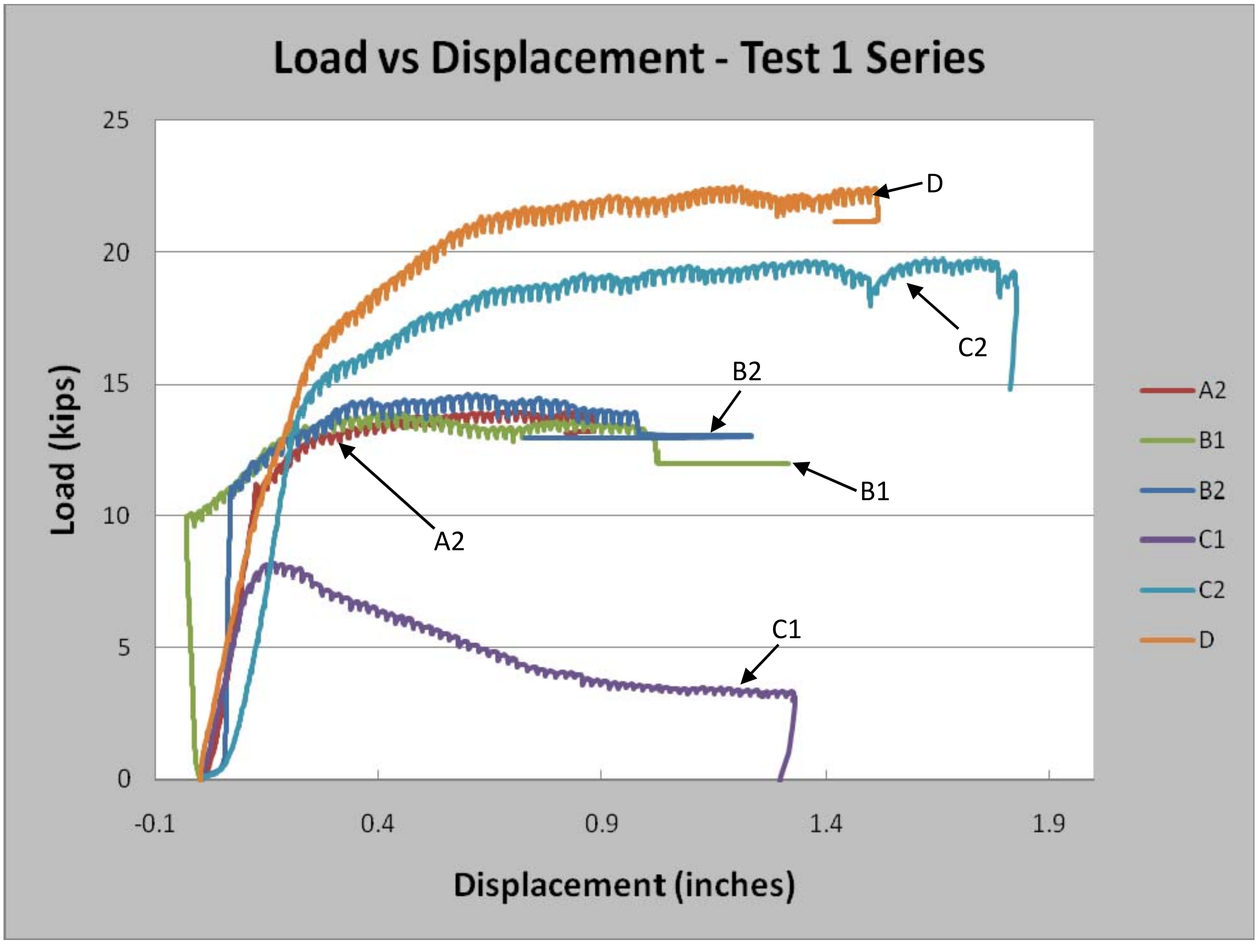


**Figure 8: Load versus Displacement - Test 1 Series**

The data for the Test 2 Series was more consistent than the preliminary testing. Figure 9 is a graph of the load versus displacement for the Test 2 Series. The maximum load, load at initial slip, and bond stresses are given in Table 1. The 18-inch specimen had an average maximum load of 40 kips, however the loads at initial slip were disparate. Two of the specimens slipped at low loads, 13.9 kips and 16.9 kips. This phenomenon was also present in specimen 9C. This early strand slip was possibly due to imperfections in the grout, especially in the longer specimens as it was difficult to remove all the voids when placing the grout. The other devices performed well in that there was no substantial increase in load after the initial slip. The maximum load for all devices was maintained for a significant length beyond the initial slip, which signifies that little or no change in bond strength occurred despite significant slippage. The average bond stress based on maximum load for the specimens was 1.36 ksi assuming a circular perimeter of $\pi$x0.5 in.; this stress is consistent among the specimens with a coefficient of variation of 3.3%.

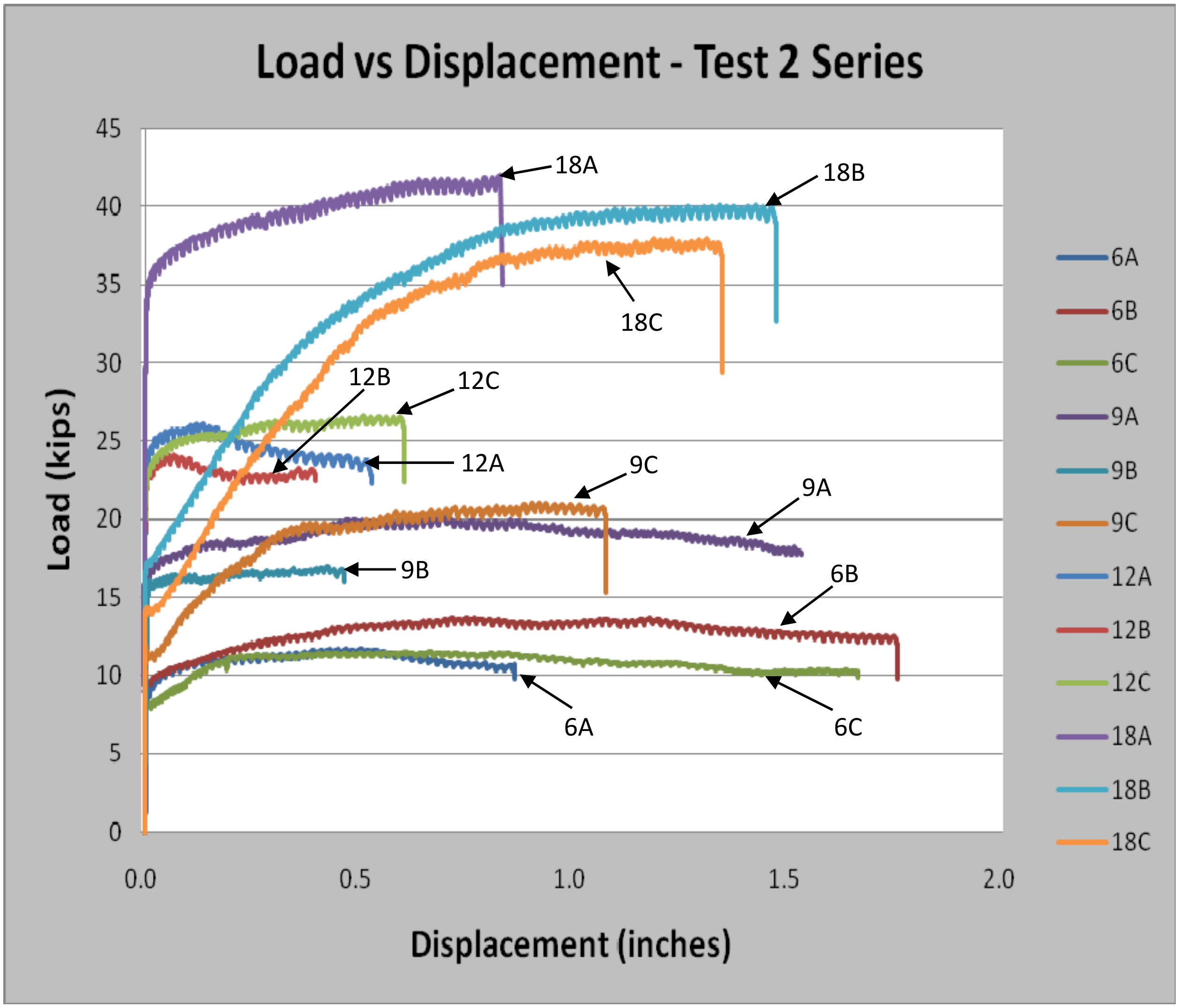


**Figure 9: Load versus Displacement - Test 2 Series**

**Table 1: Test 2 Series Data**

| Specimen | Slip Load (kip) | Max Load (kip) | Average Slip Load (kip) | Average Maximum Load (kip) | Bond Stress* (ksi) | Average Bond Stress (ksi) | Length (in.) |
|---|---|---|---|---|---|---|---|
| 6A | 8.00 | 11.75 | 8.23 | 12.32 | 1.25 | 1.31 | 6 |
| 6B | 8.80 | 13.67 | | | 1.45 | | |
| 6C | 7.90 | 11.53 | | | 1.22 | | |
| 9A | 15.80 | 20.09 | 14.30 | 19.35 | 1.42 | 1.37 | 9 |
| 9B | 15.70 | 16.93 | | | 1.20 | | |
| 9C | 11.40 | 21.02 | | | 1.49 | | |
| 12A | 23.90 | 26.09 | 22.87 | 25.58 | 1.38 | 1.36 | 12 |
| 12B | 22.20 | 24.05 | | | 1.28 | | |
| 12C | 22.50 | 26.61 | | | 1.41 | | |
| 18A | 34.50 | 41.99 | 21.77 | 40.02 | 1.49 | 1.42 | 18 |
| 18B | 16.90 | 40.12 | | | 1.42 | | |
| 18C | 13.90 | 37.95 | | | 1.34 | | |
| **Average** | | | | | | 1.36 | |

* *Bond stress based on a circular cross section and maximum load*

### *4.2 Discussion*

The results of the testing reveal the complexity of distinguishing between the three types of bond mechanisms: adhesion, friction, and mechanical restraint. The response of the device is dependent on all three mechanisms; however, obtaining the amount each contributes is complicated. The major obstacle is discerning the role of the frictional bond. Friction apparently contributes a large amount to the total bond, as signified by the small amount of load change after initial slippage. With unstressed strands the diameter has the ability to decrease in size due to minute gaps between the individual wires, which would decrease the performance of the frictional bond. However, the confinement of the device and the use of non-shrink grout could improve the frictional bond. The mechanical restraint should be minimal with the smooth surface of the strand, and adhesion does not exist once slippage occurs. The overall bond strength will be used to analyze the device; therefore, a distinction between the bond mechanisms is not pertinent. The data indicates that there is consistency among the devices in the Test 2 series based on the bond stress computed with the maximum achieved load, Table 1. This is also shown in Figure 10 with a graph of the load versus the specimen length (i.e. bond length). The linear transition reveals that bond strength is directly related to the surface area of the strand. The data from the devices with early slip is not included in this graph. The information from the graph can also be extrapolated to attain the required device length to fully develop the prestressing strand, which can be calculated as area of strand x ultimate stress = 0.153 in$^2$ x 270 ksi = 41.3 kips. In order to develop the strand with minimal initial slippage the device length would need to be approximately 21 in. The 18-inch device almost meets the fully developed force when allowing slippage. To avoid potential constructability issues, it is not viable to extend the device length beyond 12 in.

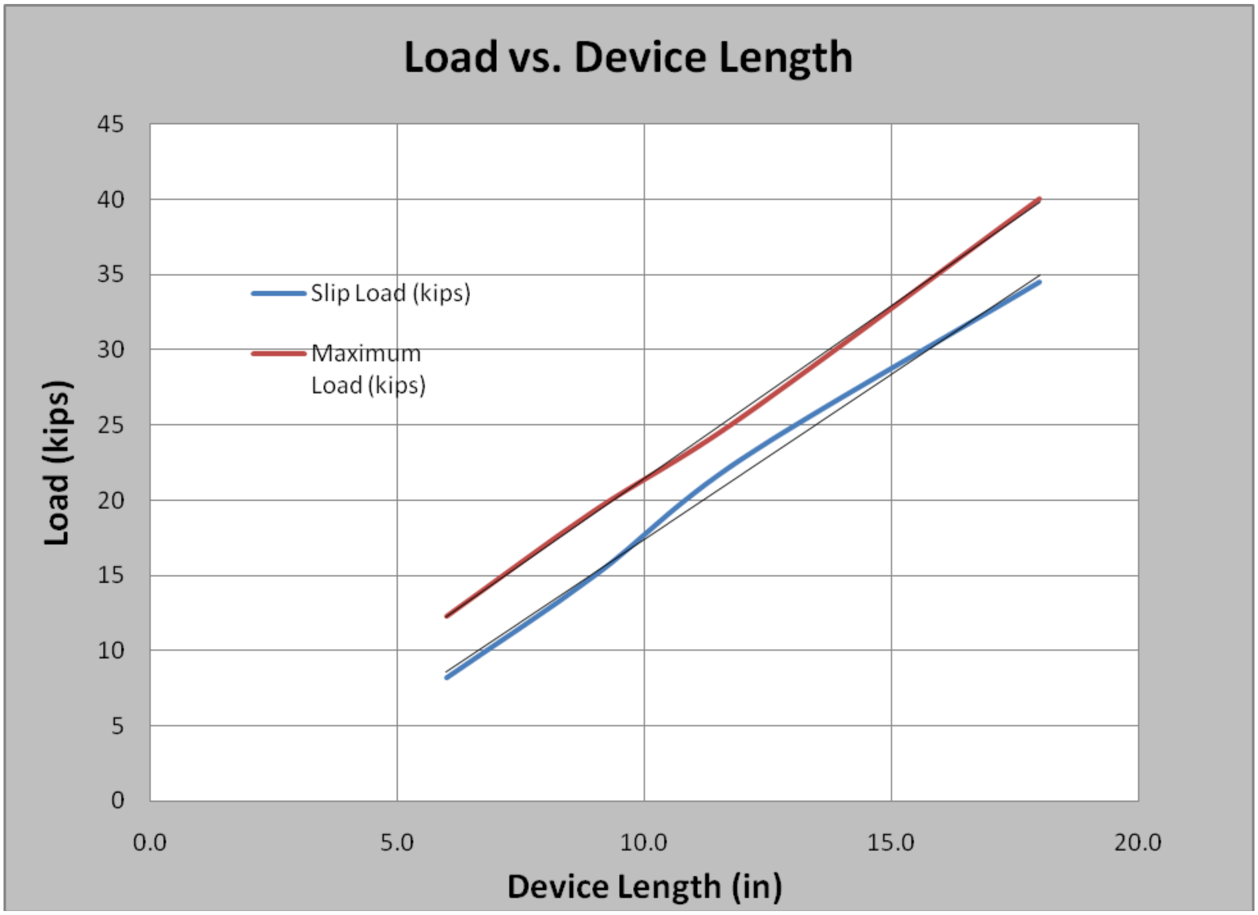


**Figure 10: Load versus Device Length – Test 2 Series**

## 5.0 Conclusions

### *5.1 Main Findings*

Designing and fabricating a grouted device to have the ability of developing the full tensile capacity of a prestressing strand proves to be very challenging with the given setup and parameters. Readily available grouting materials that are typically used for anchoring or splicing mild reinforcement do not have the capability of developing prestressing strand within a short distance of, for example, 12 in. Prestressing strand has a small surface area due to high strength steel and a smooth surface, as opposed to mild reinforcement, which significantly reduce the effect of the bond mechanisms.

### *5.2 Recommendations/ Future Research*

Based on the findings of this study, it is recommended that further research be conducted to investigate other methods of improving the bond stress between the grout and the prestressing strand. A mechanism that was not investigated in this study is the Hoyer effect, which was discussed in Section 2.1. This mechanism could potentially improve the available bond stress so that the strand is developed over the desired length. Testing the Hoyer effect would involve prestressing a strand prior to placing the grout in the device. The confinement of the device could possibly increase the effectiveness of the Hoyer effect by minimizing the amount of radial displacement of the surrounding grout due to the pressure exerted by the strand.

The use of HEM could also promote the bond stress required. Research has been conducted on the use of HEM for the anchorage of CFRP strands. This highly expansive material has the capability of producing an expansive pressure of approximately 7 ksi which should significantly increase the frictional bond between the strand and HEM. Using this material in conjunction with the Hoyer effect could also improve the bond stress. (Harada 2001)

## BIBLIOGRAPHY


American Association of State Highway and Transportation Officials (AASHTO). (2007). *AASHTO LRFD Bridge Design Specifications,* $4^{th}$ Ed., Washington, DC.

Harada, T., Khin, M., Enomoto, T., Hiroshi, K. (2001). "Development of HEM Anchorage Having Large Capacity of 2500 kN with CFRP Strands," FRPRCS-5 p. 639-648.

Janney, Jack R. (1954). "Nature of Bond in Pre-Tensioned Prestressed Concrete," *ACI Journal* Vol. 50, p. 717.

Luthi, T., Diephius, J., Icaza, J., Breen, J.E., Kreger, M.E. (2005). "Factors Affecting Bond and Friction Losses in Multi-Strand Post-Tensioning Tendons Including the Effects of Emulsifiable Oils," *Center for Transportation Research* 0-4562-1, Austin, Texas.

Lybas, J., Hoffman, V., Cook, R. A. (2003). "Effects of Strand Anchorage Devices on Shear Strength of Pretensioned Concrete Beams," PCI Journal. Vol. 48. No. 6. P. 106-115.

Rohleder, Jr., W.J., Tang, B., Doe, T.A., Grace, N.F., and Burgess, C.J. (2008). "Carbon Fiber-Reinforced Polymer Strand Application on Cable-Stayed Bridge, Penobscot Narrows, Maine," *Transportation Research Record.* No. 2050. p. 169-176.

Shahawy, M., Cai, C., (2001). "Enhancement of the Performance of Prestressed Concrete Girders Using Strand Anchorage," *PCI Journal.* Vol. 46. No. 5. p. 82-96.