COMPOSITES & PLOYCON 2009
American Composites Manufacturers Association
January 15-17, 2009
Tampa, FL USA

Durable Fiber Reinforced Polymer Bar Splice Connections for Precast Concrete Structures

by

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Abstract

The goal of this research was to develop and test alternative methods for connecting precast concrete structural members with non-metallic FRP components. Durable and non-corrosive FRP connection details were developed to be efficient and economical alternatives to current steel precast connection methods. Prototypes of FRP bar splice connections using FRP tube couplers were constructed and tested for proof of concept. Spliced FRP rebar specimens were tested in tension until failure which occurred as a result of either tube bursting, bar slip or bar rupture depending on embedment length and splice confinement. Based on laboratory experimentation it was determined that the bond stress of FRP rebar could not be reliably increased through tube splice confinement, and that a sufficient embedment length was required to develop the full tensile capacity of the FRP bars in the FRP tubes.

Introduction

Precast concrete structures provide significant advantages over cast-in-place structures, specifically in their ability to reduce construction times required and thus reducing the overall cost of the structures. The significant disadvantage of precast concrete structures is in how to connect the precast members in a safe and efficient manner. A significant number of precast members used in construction are currently jointed by spliced steel reinforcing bars (PCI 1988 and Martin and Korkosz 1982). These connections are susceptible to corrosion which could lead to deterioration of the strength of the structure. The primary cause of corrosion in steel joint connectors is exposure to sodium chloride that is present in marine environments or de-icing salts that are applied to bridge decks and parking structures.

Current steel bar splice couplers include NMB Splice-Sleeve products that were chosen for analysis based on product availability. Figure 1 shows a typical connection configuration for steel bar splice couplers.

In recent years there have been significant advancements and a general acceptance of the use of fiber reinforced polymer (FRP) materials in structural applications. The American Concrete Institute (ACI) has published a design manual for the use of FRP bars as an alternative to conventional steel reinforcing (ACI 2006). FRP materials have the potential to be viable alternatives to conventional steel joint connections because of their material properties that can give them a significant advantage over steel in terms of weight, durability, and corrosion resistance (Bank 2006). The University of Wisconsin has done extensive research in the field of fiber reinforced polymer materials and has proven that there is a potential for the use of these materials in structural applications.

Objectives of the Research

The overall goal of this research was to create durable and economical FRP connectors that were non-corrosive alternatives to current metallic connectors for joining precast concrete members. Alternative connections were examined under two broad criteria: economic viability based on FRP connection materials, and strength and durability performance of the FRP connection system. The first criterion, economic viability, governed how the alternative connections were developed and how FRP materials for these connections were selected. The second criterion, performance, was investigated for alternative connections but was not fully examined until a set of connections was fabricated and tested. These two criteria have been summarized by the following two research objectives:

1. The FRP connection components shall be competitive with current metallic connection components and shall not require any special construction practices that are overly complicated to install.
2. The connection system shall be resistant to corrosive environments and shall either perform to the strength requirements of the designated precast connection applications or shall perform to the known strength of the corresponding metallic connection counterparts.

The development of an FRP connection component that satisfies all of the research objectives listed above will benefit the precast industry, FRP manufacturers, contractors and owners. Based on the performance of the test specimens, recommendations were made as to the feasibility of these FRP connection alternatives for precast concrete members.

Connection Design Methodology

It was the intention of this research to investigate spliced FRP bars designed to resist tensile loads. These connections consisted of embedded FRP rebar in adjacent precast members that were spliced or coupled together. One member would be cast with FRP rebar protruding from its face. The other member would have embedded FRP coupling sleeves cast against its face. The protruding FRP bars would be slid into the embedded FRP tubes and grouted in place (see Figure 2). This type of connection is referred to as a splice connection or spliced sleeve connection.

A series FRP bar splice connection alternatives were developed and fabricated for in-depth laboratory investigation. This set of feasible connections was fabricated with readily available and appropriately durable FRP components from various manufactures. Glass FRP bars were provided by Hughes Brothers, Inc. located in Seward, Nebraska. FRP pultruded tubes were provided by Strongwell headquartered in Bristol, Virginia. Various other FRP mats and rovings were used to fabricate the testing specimens.

Connection designs chosen for laboratory testing were examined for proof of concept. For this reason and because of time constraints few test repetitions were completed. This research was not intended to test multiple repetitions of one particular connection design, but rather to prove whether or not the conceptual design of connecting precast concrete members with FRP components is a viable alternative to conventional steel connections.

Fabrication of Specimens

Glass FRP bars were initially tested for tensile strength, after which tensile testing was conducted on FRP bar to FRP tube splice specimens of various configurations. These splice specimens were tested under tensile loads and because of time constraints and to expedite the testing procedure FRP bar splices were not cast within concrete members. This allowed bar splice samples to be tested quickly and easily, but yielded conservative results. Bar splices were investigated for their ability to resist expansive forces of the grout within the tube splice, created by tensile loads applied to the connection. The stiffness and radial strength of the splice tube played a critical role in preventing the grout from expanding and the FRP bar from slipping. In field applications, additional confinement would be provided by the surrounding concrete.

The tensile strength of various sized GFRP reinforcing bars was examined to gage the accuracy of the testing configuration that was used for FRP bar to FRP tube splices in tension. Three samples of FRP bar sizes #4 through #10 were tested in tension until failure. Steel tubes were anchored to the bars to provide to a way to grip the specimens in the tensile testing machine.

FRP bar splice specimens were the primary focus of this research, and were tested to examine their tensile capacity and feasibility. Splice tests were primarily conducted with #6 GFRP bars to minimize variables for analysis. FRP tube splice connectors were initially chosen based on tolerances required in field applications.

Two, three foot long FRP bars were used for each specimen. One end of each of the bars was anchored with a steel tube. The other ends of FRP bars were spliced together, end-to-end in a pultruded FRP tube (Strongwell 2002). The bars were spliced together with SS Mortar grout in the FRP tube coupler. Depending on the FRP bar size used, various ¼" thick walled FRP tube sections of various lengths were used as the splice coupler. A picture of a typical bar splice specimen can be seen in Figure 3.

Two types of FRP bar to FRP tube splices were fabricated and tested: specimens with unwrapped FRP tube couplers, and specimens with wrapped tube couplers. Unwrapped tube couplers were fabricated as FRP bar splices according to the geometric properties seen in Table 1.

Wrapped tube couplers were fabricated with pultruded FRP tubes that were reinforced with additional fibers oriented in the non-primary direction to strengthen the hoop direction of the tube and to provide additional confinement of the grout in the radial direction.

As indicated by Table 1, initial bar splice specimens were fabricated with varying layers of different FRP materials. Three FRP wrapping materials were examined for this research. The first was braided fiberglass sleeves called SILASOX, manufactured by A&P Technology, Inc. Two different fiber weights were used for wrapped specimens WR-0601 and WR-0602. A second wrapping material, Fortasil 1600, manufactured by Fiber Glass Industries (FGI) was used to wrap specimen WR-0603. The final wrapping material that was used extensively throughout this research was FGI Flexstrand roving. Wrapping of FRP tube couplers was conducted on a filament winder (seen in Figure 4) in the University of Wisconsin-Madison Composite Materials Laboratory. Figure 5 shows the wrapped specimen prior to testing.

Specimen WR-06ST is included in the wrapped connection category even though the tube splice was not actually wrapped. This bar splice connection consisted of two #6 FRP bars splice together with a steel Splice-Sleeve from NMB. This specimen was fabricated and tested as a control test to examine the connection capacity of a very stiff splice coupler. It was theorized that the strength capacity of this specimen would be as high as possible for a given bar size and embedment length regardless of the amount of wrapping on an FRP tube splice. A picture of this test specimen is shown in Figure 6.

Eight additional wrapped bar splice specimens were fabricated and tested in tension with this instrumentation configuration as indicated by Table 2. For these instrumentation tests, two specimens were fabricated with embedment lengths of 5½", 7¾", 10½" and 12¾".

Instrumentation specimens were fabricated and tested in tension in order to record the stress-strain relation of the bar splices as well as slip occurring in the bar to tube connection. Strain gages and Linear Variable Differential Transformers (LVDTs) were placed on these specimens to analyze how the specimens behaved under tensile loads. Load, strain and slip displacement were recorded while running these tension tests.

Before these specimens were wrapped with the roving strand, strain gages were attached to the outer face of the FRP tubes. ¼" long strain gages were used to measure strain in the radial and longitudinal directions as indicated by Figure 7.

An LVDT was mounted onto the specimen for testing. This LVDT was attached to the wrapped FRP tube to measure differential displacement between the FRP tube and the FRP bar. Figure 8 shows the location of the LVDT on the test specimen.

Testing Procedure

The bar manufacturer defines an ultimate tensile strength for their FRP bars as a "guaranteed" tensile strength. This guaranteed strength has been determined by the bar manufacturer to be the mean tensile strength of a sample of bar specimens minus three times the standard deviation (ACI 2006). It is an important distinction to note that FRP bars do not yield as steel bars do. The guaranteed tensile strength given by the bar manufacturer is effectively the ultimate stress that the bar can withstand without failure.

Tensile testing was conducted on a 200 kip capacity machine (see Figure 8). The rate of loading was controlled using a mechanical dial on the testing machine that was set to the same value for each test. The rate of loading was controlled at approximately 10,000 lbs per 90 seconds for all tests.

Bar splice specimens were not cast within concrete members, which was their primary design function. Tested were conducted to find the potential benefit that FRP bar splice connections could have on the precast concrete industry.

The steel anchorage tubes potted to the FRP bar splice specimens allowed for the specimens to be tested in tension without gripping directly onto the bar, preventing the reinforcing fibers from being crushed by the wedge grips. It was the intent of this research to develop an FRP bar splice connection that met or exceeded the tensile stress capacity of the FRP bar. This required that the bar fail before the tube splice for the connection to be satisfactory. Because of the brittle nature of FRP materials, the failure of the specimen was anticipated to be sudden and catastrophic. This was very different from the failure mode expected with a steel reinforcing bar, which would yield and elongate substantially before failure.

Instrumentation specimens with wrapped tube couplers were testing in tension while load, strain and slip displacement data was recorded. Load was recorded from a 100 kip capacity load cell. Strains in the longitudinal and radial directions were recorded from the two strain gages on the specimen. Differential displacement between the tube and bar was recorded with the LVDT. Input from all of these devices was recorded through a portable data acquisition system. The devices attached to the specimens were used to provide a better understanding of the failure mode and capacity of the splice connections.

Experimental Results

Bar Tension Specimens

20 of the 21 FRP bar tension tests failed due to complete tensile rupture of the continuous fibers of the bar as seen by Figure 9. This failure mode represents a brittle bar failure that was sudden and catastrophic. One bar specimen failed due to slip of the grout in the steel anchorage tube. Table 3 shows the test results of the average tensile strength of the glass FRP bars of sizes #4 through #10. The test results are fairly consistent for the FRP bar sizes as indicated by the standard deviation of the ultimate tensile stresses.

Unwrapped Tube Splice Specimens

Results from unwrapped tube specimen tests are shown in Table 4. For all unwrapped tube splice specimens, failure occurred in the FRP tube, not the FRP bar. Failure occurred due to tube bursting caused by delamination of the fibers beginning at the edge of the splice. This delamination caused a crack to form in the FRP tube that propagated along the length of the tube (with the fibers of the tube) as seen in Figure 10.

Figure 11 shows the typical tube bursting failure that occurred through the thickness of the unwrapped splice tube.

Wrapped Tube Splice Specimens

The critical embedment length for Specimens WR-0601 through WR-0606 was 5½". The embedment length for specimen WR-06ST was 5.25". The two critical experimental results for these bar splice specimens were the failure mode, and the stresses that occurred in the bar at failure. The critical stresses were the ultimate tensile stress and the ultimate bond stress capacity experienced by the FRP bar at failure. These experimental results are given in Table 5.

All of the initial wrapped specimens failed due to slip between the FRP bar and the grout in the FRP tube. Specimens WR-0601 and WR-0602 failed due to bar slip as a result of cracking in the FRP tube (see Figure 12), that allowed the spliced FRP bar to slip. Figure 13 shows a picture of the typical slip failure mode that occurred in these wrapped specimens.

The behavior of Specimen WR-06ST under tensile loading was very similar to the wrapped specimens. Failure occurred due to slip between the FRP bar and the grout in the steel NMB Splice Sleeve.

The FRP wrapping materials of Specimen WR-0601 through WR-0606 remained intact and did not show any visible signs of deformation, elongation, debonding or delamination.

Instrumentation Splice Specimens

Table 6 shows the ultimate capacity and failure modes for the instrumentation specimen tests. The FRP bar splice specimens with embedment lengths of 5½" and 7¾" failed due to slip between the FRP bar and the grout in the FRP tube splice (see Figure 14). Of the two FRP bar splices with embedment lengths of 10½", one of the specimens failed due to slip between the FRP bar and the grout in the FRP tube splice and the other specimen failed due to complete tensile rupture of the continuous fibers of the FRP bar (see Figure 15). Both of the bar splices with embedment lengths of 12¾" failed due to tensile rupture of the fibers of the FRP bar.

Discussion of Experimental Results

Although the ultimate tensile stress of FRP bars is generally higher than the yield stress of steel bars, it is not necessarily higher than the ultimate stress of steel bars. For example, Aslan 100 GFRP bar of size #6 has a guaranteed ultimate tensile stress of 90 ksi. This is the stress at bar rupture failure which is an irreversible, catastrophic failure. In contrast to this a typical Grade 60, #6 steel bar has a yield stress of 60 ksi but will not experience catastrophic failure until a tensile stress of 90 ksi is applied to the bar. These differences must be considered when designing an FRP connection alternative. Throughout this research, connection alternatives have been designed and analyzed based on the guaranteed ultimate stresses of the FRP materials.

Bar Tension Specimens

Table 7 shows the results of the bar tension tests as well as the guaranteed bar strength given by the bar manufacturer. All of the bars met the ultimate stress capacity given by the bar manufacturer. The #7 GFRP bars did not perform as well as the other bars in terms of ultimate tensile capacity and it is recommended that a larger sample of this size bar specimens be tested to fully examine these discrepancies. For the other bar sizes examined (#4 through #6 and #8 through #10) the average factor of safety between the guaranteed strength and the ultimate capacity found from laboratory testing was 1.30, indicating that the manufacturer's guaranteed tensile stress is conservative.

Unwrapped Tube Splice Specimens

None of the unwrapped specimens met the guaranteed ultimate stress given by the manufacturer. The average specimen experienced only 39% of the manufacturer's guaranteed bar tension strength (see Table 8). Failure occurred in the FRP tube splice before the ultimate stress of the bars could be reached. This was because tube bursting occurred due to the radial expansion of the grout in the tube splice. Based on the results of the tension tests it was not recommended that the unwrapped FRP tubes used in this research be used as splice couplers for FRP bars. If an FRP tube with an appropriate radial stiffness and strength to effectively confine the grout within the splice is found, then it may be used as a tube splice. This research has shown that based on the ¼" thick walled pultruded tubes, additional confinement needs to be added prevent the tube from bursting.

Wrapped Tube Splice Specimens

None of the wrapped splice specimens performed to the desired manufacturer's guaranteed ultimate tensile stress (see Table 9) and because of this were considered inefficient connections. The bond capacity of the spliced FRP bar controlled the tensile capacity of these specimens as indicated by the slip failure mode that occurred between the FRP bar and the grout in the FRP tube. The results from this testing provided a basis for the design of the instrumentation splice specimens as well as an understanding of the performance of the different wrapping alternatives.

The two specimens fabricated with the SILASOX braided sleeves (Specimens WR-0601 & WR-0602) failed due to tube cracking, indicating that the fiberglass wrapping material did not provide enough confinement to prevent expansion of the grout in the splice tube. Neither of the SILASOX sleeves were rigid enough to prevent the tubes from cracking and it was not recommended that these sleeves be used as a wrapping material for FRP bar to FRP tube splice connections.

The specimen fabricated and wrapped with Fortasil 1600 (Specimen WR-0603) failed due to slip between the FRP bar and the grout in the FRP tube splice. Close examination of the FRP tube showed that there was no visible cracking in the FRP tube indicating that the Fortasil 1600 was sufficient to confine the grout in the FRP tube; however, it was not recommended as a wrapping material for FRP tube splices because it was difficult to apply to the tube in a lab environment.

Specimens WR-0604 and WR-0605 were wrapped with one layer of FGI Flexstrand roving. The bond stress capacity was the controlling factor of these two specimens. The one layer of FGI roving prevented the FRP tube from bursting and thus one layer of FGI Flexstrand was considered efficient to confine the grout in the splice tube enough to prevent tube bursting failure.

Two layers of FGI Flexstrand roving were used to wrap Specimen WR-0606. This specimen also failed due to slip between the FRP bar and the grout in the FRP tube. Failure occurred at 70.0% of the guaranteed bar strength which was the highest of any wrapped specimen tested, but was still lower than the desired capacity of the tension connections. This connection design was promising, in that the FRP tube splice was sufficient to prevent tube bursting failure, however this connection was limited by the bond stress capacity of the FRP bar.

It was anticipated that the relatively high stiffness of the steel NMB splice-sleeve compared to the FRP tube would provide a good basis for the maximum bond stress that could be achieved with multiple layers of FRP wrapping. Specimen WR-06ST failed due to slip between the FRP bar and the grout in the steel splice tube. This failure mode was similar to the above mentioned specimens (WR-0603 through WR-0606) and indicated that the bond capacity of the bar was still the controlling factor.

Regardless of the amount of confinement applied to the FRP tube, failure was determined to be controlled by the bond stress capacity of the FRP bars. To increase the capacity of the connection component, larger embedment lengths were determined to be necessary. The next section discusses the FRP bar to FRP tube splice specimens that were fabricated with various embedment lengths and examined with instrumentation.

Instrumentation Splice Specimens

As discussed above, these bar splice specimen test results should be conservative because the splices were tested in tension without being encased in concrete. A comparison of the test results and the guaranteed manufacturer's stress is shown in Table 10.

The first instrumentation specimen tested with a splice embedment of 5½" (Specimen IN-4055) failed at a bond stress that was just larger than the guaranteed bond stress capacity. The second specimen tested with a 5½" splice length achieved a significantly higher bond stress at failure, but this was due to the difference in age of the grout of these two specimens. Specimen IN-4055 was tested at a grout age of 2 days while specimen IN-6055 was tested at a grout age of 40 days. This was a significant difference in the age of the grout in the tube splice and accounts for the higher ultimate tensile and bond stresses of the specimen. Neither of these specimens were able to achieve the guaranteed tensile strength of the FRP bar and were therefore considered inadequate splice connection designs.

Both instrumentation specimens with an embedment length of 7¾" (Specimens IN-2077-A and -B) failed due to slip between the FRP bar and the grout in the FRP tube splice. Neither of these two specimens preformed to their desired capacity and it was determined from their failure mode that the bond stress capacity of the bar was the controlling factor for the splice connection. These bar splices were not recommended because they did not develop the full tensile capacity of the FRP bars.

The first specimen with a bar splice length of 10½", (Specimen IN-2105-A) failed due to slip between the FRP bar and the grout in the FRP tube splice. This failure mode indicted that the bar did not reach its full tensile capacity however it did achieve its guaranteed tensile strength given by the bar manufacturer. The second specimen with a bar splice length of 10½", (Specimen IN-2105-B) failed due to complete tensile rupture of the continuous fibers in the FRP bar at a higher ultimate stress than what was guaranteed by the manufacturer. Based on the test results, a 10½" bar splice embedment length was recommended to be used as splice connection configurations for #6 Hughes Brother FRP bars.

Both instrumentation specimens with an embedment length of 12¾" (Specimens IN-2127-A and -B) failed as a result of tensile rupture of the fibers of the FRP bar. The controlling factor for bar splices with this embedment length was the ultimate tensile strength of the FRP bar. This embedment length was greater than the minimum required to meet the guaranteed strength of the FRP bar and was considered an inefficient design because it used more materials than necessary.

Conclusions

The bar splice connections were required to meet the guaranteed ultimate tensile stress requirements given by the manufacturer in order to be considered effective connection methods. Based on laboratory test results, effective bar slice connections can be developed and used to resist tensile forces if the following criteria are met: (1) the FRP tube splice coupler is required to provide adequate radial confinement of the grout in the splice tube to prevent the FRP tube from cracking, (2) the embedment length of the FRP bar in the splice tube is required to be long enough to ensure that the bond stress capacity of the FRP bar does not control the splice connection. The second criterion is intended to ensure that failure occurs due to bar tensile failure, not slip between the FRP bar and the grout in the FRP tube.

Although testing was primarily conducted on #6 GFRP bars, these conclusions can be generalized for all FRP bar sizes from any manufacturer. These general conclusions were determined based on the following conclusions from the bar splice tests results. The bond stress capacity of FRP bars is the same for all bar sizes. Because the bond stress capacity of the FRP bars could not be increased by confining the grout in the tube splice, the embedment length of the bar splice was increased to increase the tensile capacity of the connection. The splice specimens with 5½" and 7¾" embedment lengths did not achieve the guaranteed ultimate tensile stress given by the bar manufacturer. The capacity of these specimens was controlled by the bond stress capacity of the FRP bar as evident by the slip failure mode between the FRP bar and the grout in the FRP tube splice. The bar splice specimens fabricated with 10½" and 12¾" embedment lengths achieved an ultimate tensile stress that was greater than the manufacturer's guaranteed bar strength. It was determined that a minimum embedment length of 10½" was required to achieve the guaranteed tensile strength for a #6 FRP bar. This was determined to be the critical embedment length, meaning that a shorter embedment length will not achieve the guaranteed tensile strength and that a longer embedment length will be an inefficient design for a #6 spliced FRP bar.

Acknowledgements:

I appreciate all the help and support provided by manufacturers and technical representatives. A project such as this, which involves a lot of testing, cannot be accomplished without the generous contribution of numerous individuals. Thanks to Strongwell and Hughes Brothers who provided us with the majority of the FRP products used to fabricate the connection alternatives. Thanks to NMB Splice-Sleeve who provided us with technical services and materials. Thanks to Fiber Glass Industries and A&P Technology whose FRP products were used throughout this research.

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Michael G. Oliva, Ph.D., Professor, University of Wisconsin-Madison. Michael Oliva has over thirty years of experience in the field of precast/prestressed concrete and has conducted numerous research projects directed at improving precast systems.

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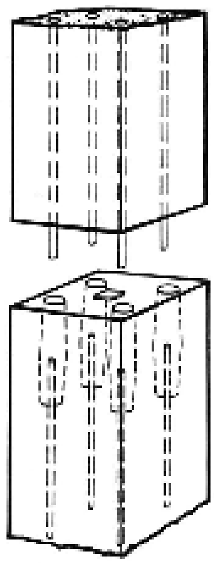

Figure 1: Steel Bar Splice Connection (Courtesy of NMB Splice-Sleeve)

Figure 5: Wrapped Tube Specimens

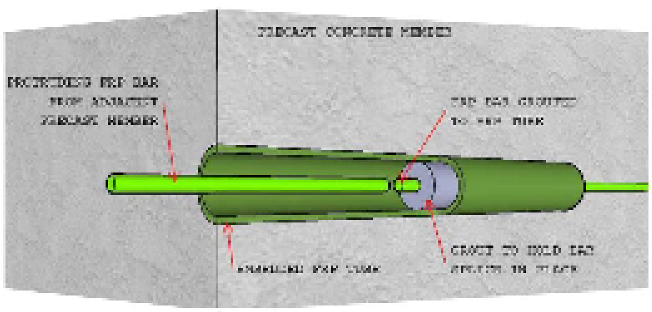

Figure 2: FRP Bar Splice Connection

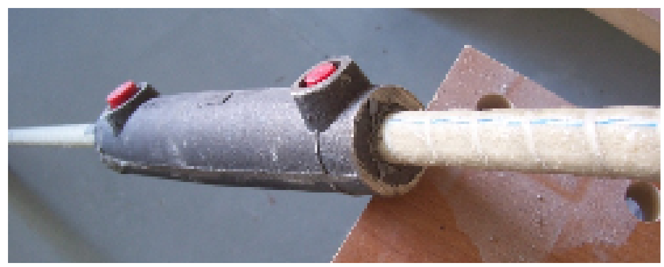

Figure 6: FRP Bar Splice with NMB Steel Splice-Sleeve (Specimen WR-06ST)

Figure 3: Typical Bar Splice Specimen

Figure 7: Location of Strain Gages on FRP Tube

Figure 4: FRP Filament Winder

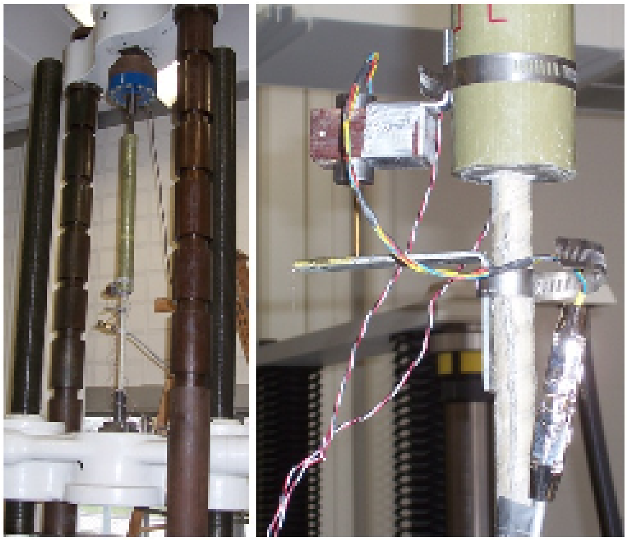

Figure 8: Instrumentation Test: (left) Configuration, (right) LVDT and Strain Gages

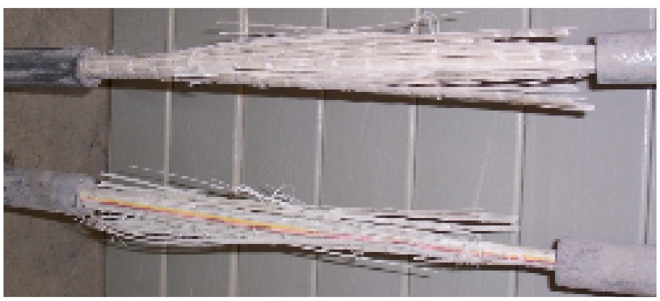

Figure 9: FRP Bar Tensile Failure

Figure 10: Specimen UW-1030 Failure Mode

Figure 11: Tube Bursting Failure in Specimen UW-0620

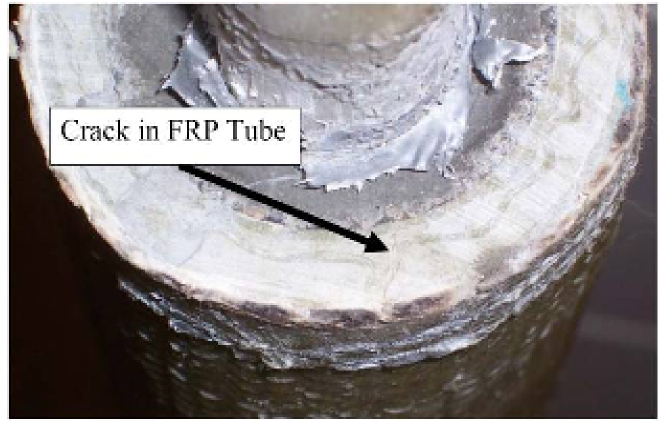

Figure 12: Crack in Tube of Specimen WR-0601

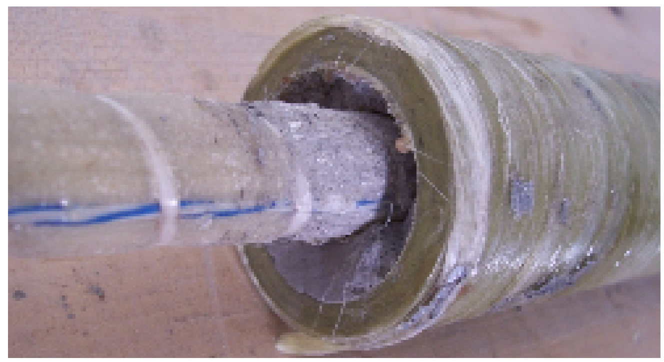

Figure 13: Specimen WR-0604 Slip Failure

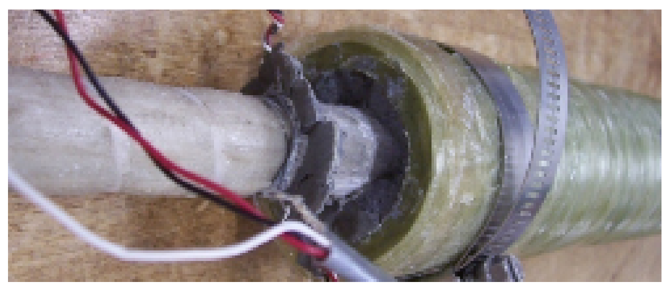

Figure 14: Specimen IN-4055 Slip Failure

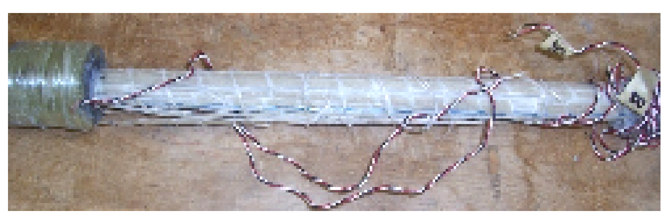

Figure 15: Specimen IN-2105-B Bar Delamination Failure

Table 1: FRP Bar Splice Specimen Properties

Specimen Type	Specimen Name	FRP Bar Size	Tube Splice O.D. (in)	Bar Splice Tolerance (in)	Embedment Length (in)	Tube Wrapping Material
Unwrapped	UW-1030	#10	3.00	1.250	8.75	None
	UW-1025	#10	2.50	0.750	8.75	None
	UW-0930	#9	3.00	1.377	8.00	None
	UW-0925	#9	2.50	0.877	8.00	None
	UW-0825	#8	2.50	1.000	7.00	None
	UW-0820	#8	2.00	0.500	7.00	None
	UW-0620	#6	2.00	0.750	5.50	None
Wrapped	WR-0601	#6	2.00	0.750	5.50	SILASOX 18.8 oz/yd^2 Sleeve
	WR-0602	#6	2.00	0.750	5.50	SILASOX 27.7 oz/yd^2 Sleeve
	WR-0603	#6	2.00	0.750	5.50	Fortasil 1600
	WR-0604	#6	2.00	0.750	5.50	1x Layer Flexstrand
	WR-0605	#6	2.00	0.750	5.50	1x Layer Flexstrand
	WR-0606	#6	2.00	0.750	5.50	2x Layer Flexstrand
	WR-06ST	#6	1.97	0.670	5.25	NMB Splice-Sleeve

Table 2: FRP Bar Splice Specimens with Instrumentation

Specimen Type	Specimen Name	FRP Bar Size	FRP Tube Splice O.D. (in)	Embedment Length (in)	# Layers of FGI Flex-strand Wrapping
Instrumentation	IN-4055	#6	2.00	5.50	4
Instrumentation	IN-6055	#6	2.00	5.50	6
Instrumentation	IN-2077-A	#6	2.00	7.75	2
Instrumentation	IN-2077-B	#6	2.00	7.75	2
Instrumentation	IN-2105-A	#6	2.00	10.50	2
Instrumentation	IN-2105-B	#6	2.00	10.50	2
Instrumentation	IN-2127-A	#6	2.00	12.75	2
Instrumentation	IN-2127-B	#6	2.00	12.75	2

Table 3: Bar Tension Test Results

FRP Bar Size	Nominal Bar Diameter (in)	Nominal Bar Area (in^2)	Tensile Strength (kip) Average of 3 tests	Ultimate Tensile Stress (ksi) Average of 3 tests	Standard Deviation
#4	0.500	0.196	26.6*	135.3*	8.46*
#5	0.625	0.307	38.1	124.0	4.18
#6	0.75	0.442	47.1	106.7	2.40
#7	0.875	0.601	50.7	84.3	2.80
#8	1.000	0.785	89.9	114.5	0.65
#9	1.125	0.994	100.3	100.9	5.08
#10	1.250	1.227	101.2	82.5	2.98

* Because slip failure occurred in one #4 specimen, average results are for 2 specimens test results

Table 4: Unwrapped Tube Specimen Test Results

Specimen Name	Date Cast	Date Tested	Ultimate Capacity (kips)	Ultimate Stress (ksi)	Failure Mode
UW-1030	1/8/2008	1/17/2008	33.0	26.9	Tube Bursting
UW-1025	1/8/2008	1/17/2008	42.5	34.6	Tube Bursting
UW-0930	1/8/2008	1/17/2008	26.7	26.9	Tube Bursting
UW-0925	1/9/2008	1/17/2008	21.9	22.0	Tube Bursting
UW-0825	1/8/2008	1/17/2008	24.6	31.3	Tube Bursting
UW-0820	1/9/2008	1/17/2008	24.5	31.2	Tube Bursting
UW-0620	2/7/2008	2/11/2008	17.0	38.4	Tube Bursting

Table 5: Wrapped Tube Specimen Test Results

Specimen Name	Date Cast	Date Tested	Ultimate Capacity (kips)	Ultimate Stress (ksi)	Bond Stress Capacity (ksi)	Failure Mode
WR-0601	1/30/2008	2/11/2008	19.95	45.2	1.539	Tube Cracking
WR-0602	1/30/2008	2/11/2008	21.65	49.0	1.671	Tube Cracking
WR-0603	1/30/2008	2/11/2008	26.55	60.1	2.049	Bar Slip
WR-0604	2/7/2008	2/11/2008	23.05	52.2	1.779	Bar Slip
WR-0605	2/13/2008	2/15/2008	19.40	43.9	1.497	Bar Slip
WR-0606	2/7/2008	2/11/2008	27.85	63.0	2.149	Bar Slip
WR-06ST	2/13/2008	2/15/2008	19.20	43.5	1.552	Bar Slip

Table 6: Instrumentation Test Results

Specimen Name	Embedment Length (in)	Ultimate Capacity (kips)	Ultimate Stress (ksi)	Bond Stress Capacity (ksi)	Failure Mode
IN-4055	5.50	23.83	53.9	1.84	Bar Slip
IN-6055	5.50	34.30	77.6	2.65	Bar Slip
IN-2077-A	7.75	30.15	65.8	1.65	Bar Slip
IN-2077-B	7.75	34.38	75.1	1.88	Bar Slip
IN-2105-A	10.50	44.57	97.3	1.80	Bar Slip
IN-2105-B	10.50	46.85	102.3	N.A.	Bar Delamination
IN-2127-A	12.75	51.85	113.2	N.A.	Bar Delamination
IN-2127-B	12.75	47.35	103.4	N.A.	Bar Delamination

Table 7: FRP Bar Tension Test Discussion

		Ultimate Tensile Stress		
FRP Bar Size	Nominal Bar Area (in^2)	Average From Tests (ksi)	Guaranteed Strength (ksi)	Factor of Safety
#4	0.196	135.3	100	1.35
#5	0.307	124.0	95	1.31
#6	0.442	106.7	90	1.19
#7	0.601	84.3	85	0.99
#8	0.785	114.5	80	1.43
#9	0.994	100.9	75	1.35
#10	1.227	82.5	70	1.18

Table 8: Unwrapped Specimen Test Discussion

			Ultimate Tensile Stress		
Specimen Name	Failure Mode	FRP Bar Size	From Tests (ksi)	Guaranteed Strength (ksi)	% of Guaranteed
UW-1030	Tube Bursting	#10	26.9	70	38.4%
UW-1025	Tube Bursting	#10	34.6	70	49.5%
UW-0930	Tube Bursting	#9	26.9	75	35.8%
UW-0925	Tube Bursting	#9	22.0	75	29.4%
UW-0825	Tube Bursting	#8	31.3	80	39.2%
UW-0820	Tube Bursting	#8	31.2	80	39.0%
UW-0620	Tube Bursting	#6	38.4	90	42.6%

Table 9: Wrapped Tube Specimen Test Discussion

			Ultimate Tensile Stress (90 ksi)		Bond Stress Capacity (1.679 ksi)	
Specimen Name	Tube Wrapping Material	Failure Mode	From Tests (ksi)	% of Guaranteed	From Tests (ksi)	% of Guar-anteed
WR-0601	SILASOX 18.8 oz/yd^2 Sleeve	Tube Cracking	45.2	50.2%	1.539	91.7%
WR-0602	SILASOX 27.7 oz/yd^2 Sleeve	Tube Cracking	49.0	54.5%	1.671	99.5%
WR-0603	Fortasil 1600	Bar Slip	60.1	66.8%	2.049	122.0%
WR-0604	1x Layer Flexstrand	Bar Slip	52.2	58.0%	1.779	105.9%
WR-0605	1x Layer Flexstrand	Bar Slip	43.9	48.8%	1.497	89.2%
WR-0606	2x Layer Flexstrand	Bar Slip	63.0	70.0%	2.149	128.0%
WR-06ST	NMB Splice-Sleeve	Bar Slip	43.5	48.3%	1.552	92.4%

Table 10: Instrumentation Bar Splice Test Discussion

			Ultimate Tensile Stress (90 ksi)		Bond Stress Capacity (1.679 ksi)	
Specimen Name	**Failure Mode**	**Embedment Length (in)**	**From Tests (ksi)**	**% of Guar-anteed**	**From Tests (ksi)**	**% of Guaran-teed**
IN-4055	Bar Slip	5.50	53.9	59.9%	1.84	109.5%
IN-6055	Bar Slip	5.50	77.6	86.2%	2.65	157.6%
IN-2077-A	Bar Slip	7.75	65.8	73.1%	1.65	98.3%
IN-2077-B	Bar Slip	7.75	75.1	83.4%	1.88	112.1%
IN-2105-A	Bar Slip	10.50	97.3	108.1%	1.80	107.3%
IN-2105-B	Bar Delamination	10.50	102.3	113.7%	N.A.	N.A.
IN-2127-A	Bar Delamination	12.75	113.2	125.8%	N.A.	N.A.
IN-2127-B	Bar Delamination	12.75	103.4	114.9%	N.A.	N.A.