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CHARACTERIZATION OF CFRP RODS USED AS NEAR-SURFACE MOUNTED REINFORCEMENT

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ABSTRACT

Carbon Fiber Reinforced Polymer (CFRP) bars have many applications in the field of civil engineering. They are used as reinforcement in new construction for both reinforced concrete and prestressed concrete structures. They are also used for repair/rehabilitation of concrete structures in the form of near-surface mounted reinforcement. This paper focuses on the characterization of the CFRP bars for their application as near-surface mounted reinforcement. In particular, the tensile capacity and bond strength of the CFRP bars were investigated. To determine tensile capacity of the bars, longitudinal tensile tests were performed. In order to perform the tensile test, anchors had to be developed for gripping the bar. The testing procedure was based on the provisional specification for FRP bar test method. Characterization of the bond strength of the bars was accomplished by performing pullout tests. Different bonded lengths were investigated. The limitations of the test method are discussed along with recommendations for future work.

INTRODUCTION

The use of near-surface mounted FRP bars as reinforcement to concrete is a new and promising technology. This technology is suitable for the repair/rehabilitation of concrete structures and has similarity to externally bonded reinforcement sheets. It is useful for improving the flexure and shear capacity of structural members. The method used in applying the near-surface mounted bars is described as follows. A groove is cut into the concrete surface allowing approximately 1/8 in (3 mm) clearance around the bar. The groove is then filled with an epoxy paste, and the bar is placed in the groove ensuring it is completely covered with the paste. Advantages of using the near-surface mounted bars are in the possibility of anchoring the reinforcement into adjacent RC members, and minimal surface preparation work and installation time (Nanni et al., 1999).

Test methods are needed to ensure that the FRP bars used in near-surface mounted application have adequate tensile and bond strength. Test methods for each case have been developed and evaluated. The tests will be referred to as the tensile and bond tests. Each of these tests will be discussed, and recommendations will be made.

TENSILE TEST

The CFRP bar longitudinal tensile tests were performed in order to determine the feasibility of using bars produced by US fabricators. It is known that CFRP bars available are proprietary in nature. They have various mechanical properties due to their different fiber type and content, matrix type, and method of production [Gilstrap, 1997). An understanding of their tensile performance is necessary for their application as near-surface mounted reinforcement. CFRP bars made of fibers produced by three major carbon fiber manufacturers (Zoltek, Toray, and Grafil) and two fabricators were tested.

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Tensile Specimens

A total of 24 specimens were tested in this program. The bars tested were manufactured by pultrusion technique, and had a diameter of either 5/16-in (8-mm) or 7/16-in (11-mm). Three types of bar surfaces were used. Thirteen specimens had smooth surface. Nine specimens were roughened by the manufacturers using a sandblasting technique. The sandblasting machine consisted of a 185-CFM (cubic foot per minute) (5.24 cubic meter per minute) compressor which was set at 90-psi (0.62 MPa) air pressure, a 300 lb. (136-kg) sandpot with a ¼ -in (6-mm) nozzle. The blast aggregate was medium grade Black Beauty which is a blast furnace deposit material containing 47% of silicon dioxide. The production rate was 1.5-ft (457-mm) per minute. The surface roughness was judged by visual inspection. The prepared surface profile was defined as: the sheen coating is removed, and some fibers are exposed without damage. Two specimens were roughened by applying a peel-ply that, when removed, resulted in indentation to the bar surface [Gilstrap, 1997].

The specimens were classified into 4 series, known as Z series, G series, T series and S series. Each specimen was given a code depending on the bar diameter (5, 7), fiber type (Z, G, T), surface condition (S, R, P) and the number of repetitions. For example, 5-Z-S-1 represents the specimen that has 5/16-in (8-mm) diameter, being made of Zoltek fibers, its surface is sandblasted and it is the first repetition; 7-T-R-3 represents the third 7/16-in (11-mm) diameter specimen made of Toray fibers with manually roughened surface. Table 1 gives the material properties of test specimens as represented by the manufacturers' data sheets.

Table 1: CFRP Bar Material Properties from Manufacturer

Specimen Series	Z Series				G Series	T Series	S Series
Bar Diameter (in)	5/16		7/16		7/16	7/16	5/16
Fiber Designation	Panex 33	Grafil 34-700	Panex 33	Grafil 34-700	Grafil 34-700	T700S	Grafil 34-700
Tow Size	48K	12K	48K	12K	48K	24K	Not Known
Fiber Tensile Strength (ksi)	525	640	525	640	640	700	650
Fiber Tensile Modulus (ksi)	33000	33500	33000	33500	33500	33000	34000
Fiber Elongation (%)	1.7	1.9	1.7	1.9	1.9	2.1	1.9
Fiber Volume Fraction (%)	63.6	1.8	63.6	1.8	66.5	65.8	65.0
Resin Type	Shell Epoxy 9300 Series		Shell Epoxy 9300 Series		Shell Epoxy 9300 Series	Shell Epoxy 9300 Series	Shell Epoxy 9405
Neat Resin Tensile Strength (ksi)	11		11		11	11	9.3
Resin Tensile Modulus (ksi)	453		453		453	453	401
Filler and Additives	Proprietary		Proprietary		Proprietary	Proprietary	Proprietary

Note: 1 in = 25.4 mm; 1 ksi = 6.895 MPa

The specimens identified as Z series contained 48K Zoltek fiber tows and 12K Grafil fiber tows in order to meet the target fiber volume fraction. The two specimens of S Series identified as 5-G-P-1 and 5-G-P-2 were generic bars designed and fabricated as control specimens for comparative purpose. The bars have diameter of 5/16-in (8-mm). The surface of bar was indented by applying a peel-ply during pultrusion. The test results for the S series bars were used as a benchmark to evaluate the performance of other specimens and to verify the test method.

An essential requirement for conducting tensile tests is a suitable anchor device to grip the specimens without causing slippage or premature local failure during the test. The conventional method to run a tensile test for a steel specimen is to grip the specimen directly with the steel jaws of the test machine. However, this method does not apply for FRP bar tensile testing. The reason is that FRP bars are sensitive to compressive forces in the transverse direction. The ratio of the bars' longitudinal tensile and transverse compressive strength is more than 10:1, the first is controlled by fiber properties and the second is controlled by resin. The stress concentration due to gripping can easily crush the specimen and result in premature failure. A grouted anchor consisting of a steel pipe filled with expansive grout was utilized in this project [Dye et al., 1998]. The internal pressure due to expansion of the grout restrained the bar from slipping out of the pipe when direct tension was applied. This type of anchorage device distributes the gripping force to a much larger area of bar surface and may prevent premature failure. Three different types of steel pipe were used for anchoring in order to optimize their dimensions. The dimensions of the pipes are given in Table 2.

Table 2: Dimension of Anchor Pipe

	Length (in)	Outside Diameter (in)	Inside Diameter (in)	Wall Thickness (in)
Type I	13	1.315	1.0	0.158
Type II	18	1.66	1.28	0.19
Type III	18	1.66	1.38	0.14

Note: 1 in = 25.4 mm

Type I pipes were applied only on small diameter bars. Type II and type III pipes were installed on 7/16-in (8-mm) diameter specimens. Their longer length provided higher bond capacity and the larger inside diameter allowed them to accommodate more expansive grout, which created larger gripping force. Type III pipe had smaller wall thickness than that of type II. The reduced wall thickness caused yielding of the pipe. The details are given later in this paper.

BRISTAR 100 expansive cement was used as grout. It was mixed according to manufacturer's instructions with a water-to-cement ratio by weight of 0.29. The grout was mixed for 2 minutes. After the bar had been carefully aligned and centered inside the pipe, the cement was poured within 5 minutes. After pouring, the specimens were allowed to set for 72 hours before testing.

The total length of all test specimens was 5-ft (1.52-m), which included test section and anchoring section (see Figure 1). The test section length of the specimens was larger than the minimum requirements suggested [Benmokrane et al., 1999], which indicates the greater of 4-in (100-mm) or 40 times the nominal diameter of FRP bar.

Surface preparation of the bars was made only for the case when the bars had smooth surface. The smooth surface was roughened with 100-grit sandpaper by hand to such a degree that the surfacing material was removed and the fibers were exposed without damage.

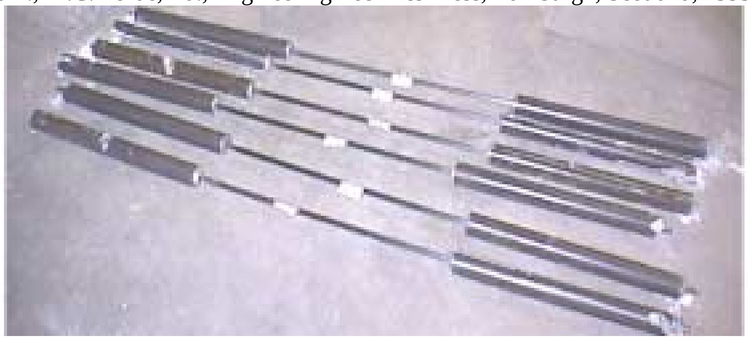


Figure 1: Specimens Ready for Test

Tensile Test Setup and Data Acquisition

Tensile tests were performed using a Universal Testing Machine. The specimen was set-up across the two cross-heads of the machine and aligned with the axis of the grips of the machine. The anchor at one end rested on the top cross-head. A ¾-in (19-mm) thick steel plate with a slot on it was inserted between the anchor and the cross-head to distribute the load. An identical plate was attached at the lower end of the bar for the same purpose. The movable cross-head of the testing machine was positioned so that the plate at the lower end was snug without stressing the bar. An electronic extensometer with 2-in (51-mm) gage length and 1/1000-in (0.025-mm) accuracy was mounted on the center of the specimen test section to measure displacement (see Figure 2).

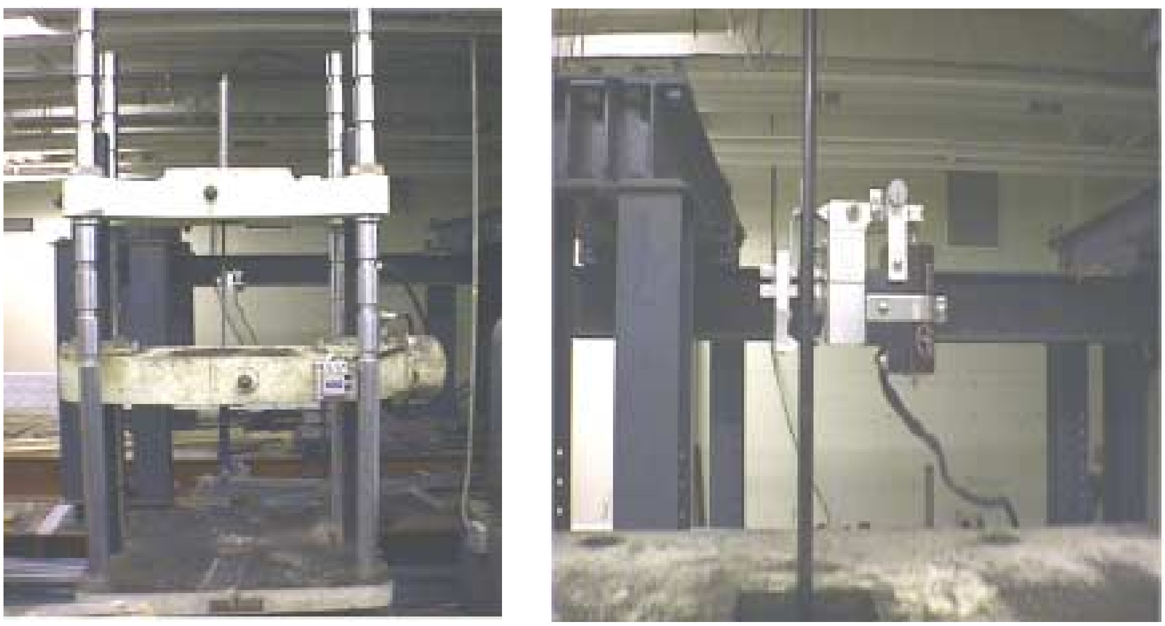


Figure 2: Tensile Test Setup

Test Procedure

The test was performed in the displacement control mode. The loading was applied at a rate of 5-kips (22-kN) per minute, which in terms of stress was 65-ksi (448-MPa) per minute for 5/16-in (8-mm) diameter bar and 33-ksi (228-MPa) for 7/16-in (11-mm) diameter bar. Both rates were within the range of loading rate recommended [Benmokrane et al, 1999], which is between 14.5-ksi (100-MPa) and 72.5-ksi (500-MPa). The test lasted from 2 to 7 minutes depending on the strength of the specimen.

Recommended practice [Benmokrane et al., 1999] indicates that the test should end with tensile failure, and the measurements are recorded until the strain reaches at least 60% of the tensile capacity or the guaranteed tensile capacity. However, for safety purpose, the extensometer was removed at 1/3 of the calculated specimen tensile capacity. The load-displacement curves were extrapolated from that point based on the ultimate load and experimental modulus of elasticity.

Test Results

Experimental tensile strength, modulus of elasticity and ultimate strain were computed from load and displacement recorded from the test and the nominal cross-sectional area of the bar. Test results are summarized in Table 3. Note that the modulus of elasticity was calculated using regression analysis within the range of 1000με-3000με, which is recommended by ASTM for typical carbon/epoxy materials.

Table 3: Summary of Tensile Test Results

Series	Specimen I.D.	Ultimate Load (kips)	Ultimate Stress (ksi)	Ultimate Strain (%)	Modulus of Elasticity (ksi)	Anchor Pipe Type	Failure Mode
Z Series	5-Z-S-1	13.12	166.7	0.96	17333	I	Tensile
	5-Z-S-2	12.29	156.1	1.00	14198	I	Tensile
	5-Z-S-3	14.46	183.6	1.02	17163	I	Tensile
	5-Z-S-4	8.36	108.9	0.69	15804	I	Tensile
	5-Z-S-5	10.03	130.7	0.78	16758	I	Tensile
	5-Z-S-6	8.96	116.7	0.79	14622	I	Tensile
	5-Z-S-7	10.96	142.9	0.84	16935	I	Tensile
	7-Z-R-1	22.72	151.5	0.92	16650	III	Combined Tensile and Bending
	7-Z-R-2	21.79	144.8	0.88	16225	III	Combined Tensile and Bending
	7-Z-R-3	27.47	183.1	1.03	17333	III	Tensile
	7-Z-R-4	26.26	175.1	1.03	16537	III	Tensile
G Series	7-G-R-1	15.30	103.5	0.51	20254	II	Bar Pullout at Bar-grout Surface
	7-G-R-2	14.70	99.4	0.49	20469	II	Bar Pullout at Bar-grout Surface
T Series	7-T-R-1	13.63	92.2	0.48	19219	II	Bar Pullout at Bar-grout Surface
	7-T-R-2	15.04	101.7	0.51	19950	II	Bar Pullout at Bar-grout Surface
	7-T-R-3	27.00	180.0	0.91	19693	II	Bar Pullout at Bar-grout Surface
	7-T-R-4	27.50	183.5	0.98	18491	II	Bar Pullout at Bar-grout Surface
	7-T-R-5	24.39	162.6	0.82	19920	II	Bar Pullout at Bar-grout Surface
	7-T-R-6	28.40	189.3	0.94	19935	II	Tensile
	7-T-R-7	28.67	191.1	0.94	20380	II	Tensile
	7-T-S-1	31.68	211.2	1.05	23735	II	Bar Pullout at Bar-grout Surface
	7-T-S-2	31.54	208.5	1.00	20759	II	Bar Pullout at Bar-grout Surface

S Series	5-G-P-1	21.74	280.5	1.26	21700	I	Tensile
	5-G-P-2	20.74	267.6	1.20	21700	I	Tensile

Note: 1 in = 25.4 mm; 1 kips = 4.448 kN; 1 ksi = 6.895 MPa

Discussion

Specimen failure in this test program occurred in three modes, namely, tensile failure, pullout failure and combined tension and bending failure.

Tensile failure can be described as an abrupt failure where fibers break and the bar completely ruptures around a cross-section within the test section. Tensile failure indicated the bar had developed its full tensile capacity, and the anchor was efficient.

Bar pullout failure occurs when the bar slips out of the anchor. A significant reduction of load can be seen while the major slippage happens. This failure mode might be attributed to one or more of the following reasons:

- High tensile capacity of the CFRP bars. The specimens failed by bar pullout were all 7/16-in (11-mm) diameter. It is difficult to obtain a load higher than 32-kips (142-kN) with this kind of anchor system.
- Insufficient curing time for the grout. Some specimens were cured for 48 hours, which was shorter than 72 hours required by the specification in order to find out if there was a great reduction of bond capacity due to shortened curing time. This explains the excessively low ultimate load for specimen 7-G-R-1, 7-G-R-2, 7-T-R-1 and 7-T-R-2, which were cast in one occasion and cured for 48 hours.
- The hand-roughened bar surface did not provide sufficient interlock.

Combined tension and bending failure happens at a section that is close to the anchor region. The explanation of this type of failure is that the pipe that had a thin wall yielded at the bottom end under longitudinal compression during testing. The local yielding of steel caused a large deformation at the yielded region and created a bending moment on the bar section close to the entrance of the pipe. The combination of tension and bending moment reduced the capacity of bar and finally resulted in premature failure.

All specimens behaved linearly elastic up to failure no matter what the failure mode was. For specimens that failed prematurely in the form of bar pullout or combined tension and bending, their ultimate stress and strain were not used for further analysis because the specimens did not develop their full tensile strength. Considering only the specimens failed by tension, the ultimate strain were lower than theoretical calculations based on the law of mixture and the constituent material nominal properties. Table 4 summarized the material property translation factors of the specimens failed by tension. The translation factors are defined as the ratio of experimental to theoretical values. The strain translations of all specimens were within the range of 40% and 70%, which were low compared to that of typical carbon composites (80-85%). In terms of stiffness translation, T series and G series exhibited translation factors larger than 90% which were reasonable, yet other series had much lower translation factors (65-80%). The low material property translations might be related to the low performance of raw materials that did not match the data given by the manufacturers.

Table 4: Translation of Material Properties

Series	Specimen ID	Strain Translation (%)	Modulus of Elasticity Translation (%)
Z Series	5-Z-S-1	57.8	80.3

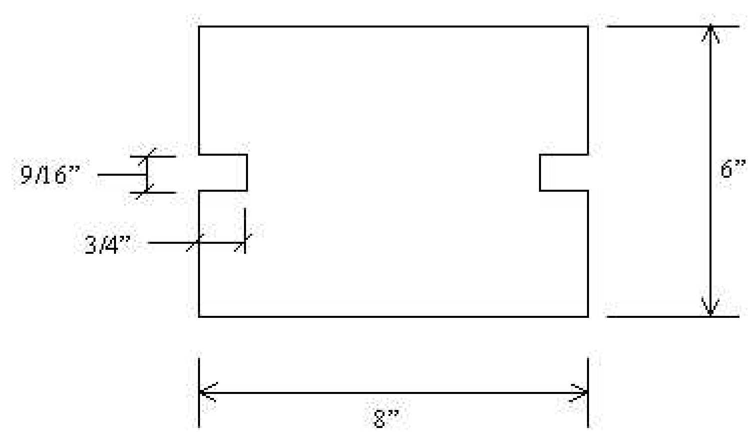
	5-Z-S-2	60.2	65.8
	5-Z-S-3	61.4	79.5
	5-Z-S-4	41.6	73.2
	5-Z-S-5	47.0	77.6
	5-Z-S-6	47.6	67.7
	5-Z-S-7	50.6	78.4
	7-Z-R-3	62.0	80.3
	7-Z-R-4	62.0	76.6
T Series	7-T-R-6	44.8	91.8
	7-T-R-7	44.8	93.9
S Series	5-G-P-1	66.3	97.4
	5-G-P-2	63.2	97.4

BOND TEST

In order to characterize the bond strength of the near-surface mounted CFRP bars, pullout tests were performed. The reason the bond is important is that it is the means for stress transfer from the concrete to the CFRP bars. The objective of this testing was to develop a bond test method for near-surface mounted reinforcement and to determine how the bonded length affected the bond strength.

<u>Bond Test Specimen</u>

The specimen used for this test consisted of two concrete blocks, two CFRP bars, and epoxy paste. The cross-section dimensions of the concrete blocks are shown in Figure 3. The depth of the block is 6 in (152 mm). The strength of the concrete used can be seen in Table 5. Only one type of CFRP bar was used for the bond testing. It was the same rod as the 7-Z-R series except it was sandblasted to improve the bonding surface as discussed earlier. The epoxy used for bonding the CFRP bar to the concrete was Concressive Paste LPL, which is manufactured by Master Builders Technologies. It is a two-part epoxy with a Part A (resin) and Part B (hardener) which are mixed in proportions of 2 parts A and 1 part B by volume. The specimens were prepared by filling the groove with the epoxy paste and then placing the bar in the paste. The paste was allowed to cure for 14 days at room temperature before testing. A description of the specimens is shown in Table 5.



Note: 1 in = 25.4 mm

Figure 3: Dimensions of Concrete Block

Table 5: Description of Bond Specimens

Specimen	Bar Diameter	Bonded Length	Concrete Compressive

	(in)	(in)	Strength (psi)
2-1	7/16	2	5250
2-2			
4-1		4	5000
4-2			
4-3			
6-1		6	5250
6-2			

Note: 1 in = 25.4 mm; 1 psi = 6.895 kPa

<u>Bond Test Procedure</u>

The test setup for the specimens can be seen in Figure 4. As can be seen, a frame was fabricated in order to test the specimens. The frame was placed in a universal testing machine, which was used to apply a tensile force to the bars while the frame restrained and supported the block. LVDTs were mounted on the specimen in order to measure the slip of the bars. The specimens were loaded at a rate of 1 kip (4.45 kN) per minute until one of the bars slipped. Equal loading on both sides was ensured because the slippage of the bars is on the order of 1 milli-inch (0.025 mm) and the spreader beam can rotate enough to compensate for this amount of slippage.

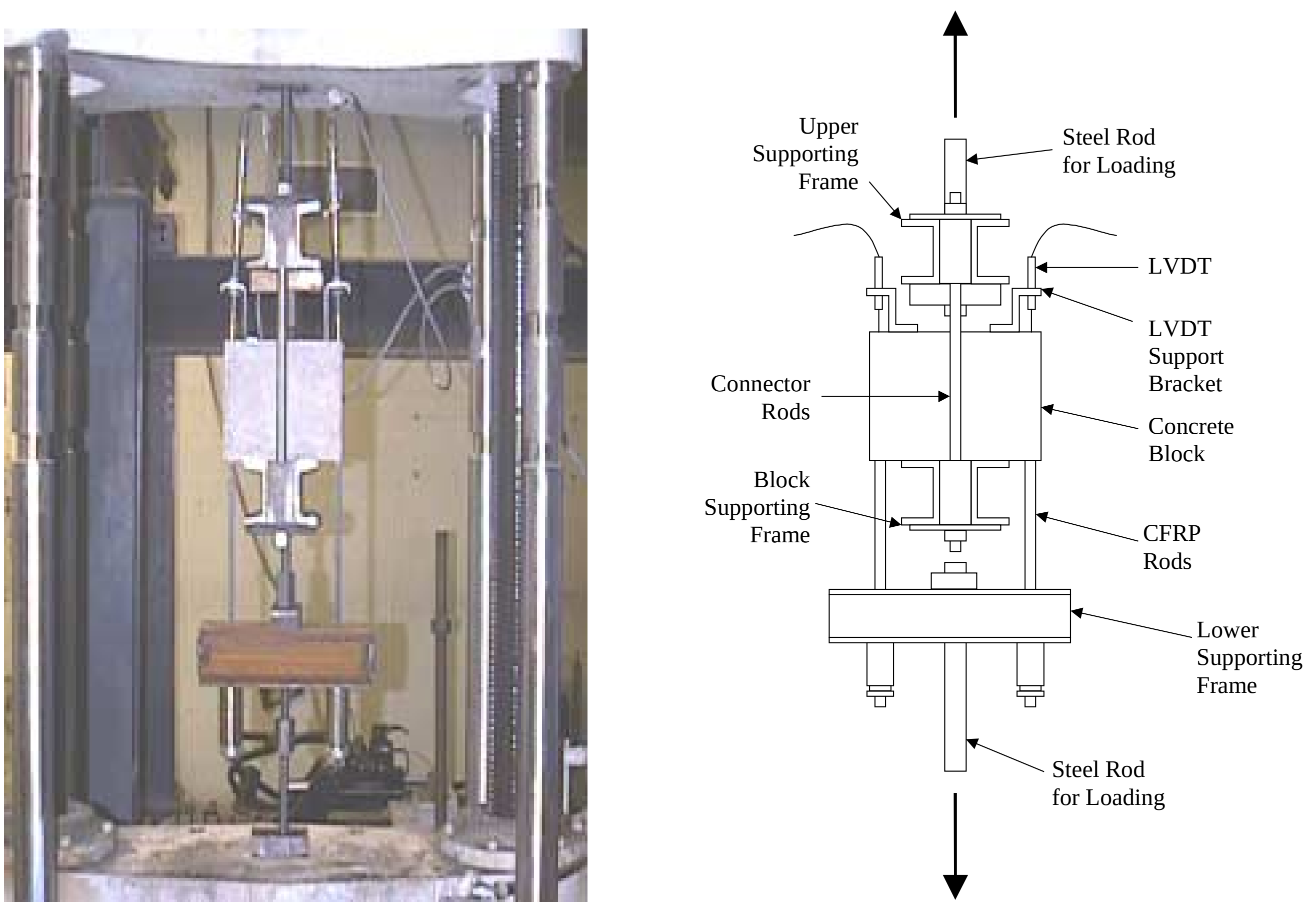


Figure 4: Bond Test Setup

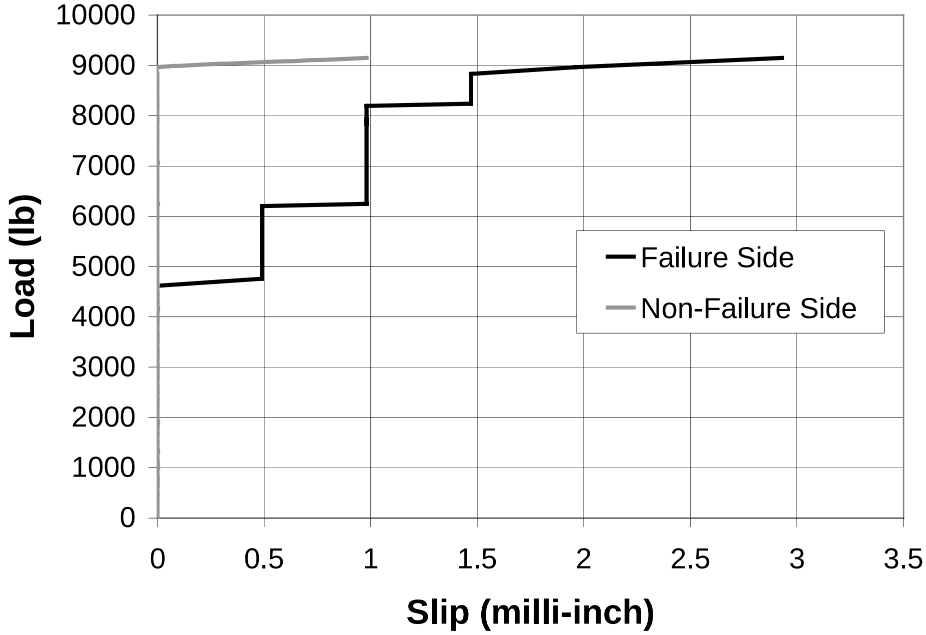
Bond Test Results

The results of interest, which are shown in Table 6, are the load at slip, the ultimate load, free-end slip, and failure mode. The loads are also converted to bond stresses at both the concrete-epoxy and bar-epoxy interface. It can be seen that the ultimate load increased considerably when the bonded length increased from 2 to 4 in. (51 to 102 mm). However, the increase was small when comparing the 4 and 6 in (102 and 152 mm) bonded lengths. In Figure 5, a load vs. slip diagram is shown. The slip was measured using LVDTs that were mounted as shown in the test setup. There are two curves shown on the graph, one for each bar. It can be seen that one of the bars slipped prior to the other bar, and this is also the side of the specimen that failed. There were two types of failure modes that occurred in the specimens. One failure mode occurred due to concrete rupture (see Figure 6), and the other occurred in the bar-epoxy interface (see Figure 7). Except for specimen 2-1, only specimens with the 6-inch (152-mm) bonded length failed by slippage at the bar-epoxy interface. This is because the area of concrete resisting the force transmitted by the bar increases as the bonded length increases.

Table 6: Results of Bond Tests

Specimen	At Onset of Slip			Ultimate				
	P_{max} (lb.)	τ (psi)		P_{max} (lb.)	τ (psi)		Free-end Slip (milli-in)	Failure Mode
		Concrete-Epoxy	Bar-Epoxy		Concrete-Epoxy	Bar-Epoxy		
2-1	1982	529	721	2174	580	791	2.93	Bar-epoxy
2-2	886	236	322	1981	528	720	2.93	Concrete
4-1	2287	305	416	4574	610	832	2.9	Concrete
4-2	N/A	N/A	N/A	5002	667	910	N/A	Concrete
4-3	2808	375	511	4257	550	750	2.0	Concrete
6-1	N/A	N/A	N/A	5015	446	608	N/A	Bar-epoxy
6-2	4188	372	508	5759	512	698	2.93	Bar-epoxy

Note: 1 in = 25.4 mm; 1 lb = 4.45 N; 1 psi = 6.89 kPa



Note: 1 inch = 25.4 mm; 1 lb = 4.45 N

Figure 5: Load vs. Slip

Figure 6: Failure in Concrete

Figure 7: Failure in Bar-Epoxy Interface

CONCLUSIONS

For the tensile characterization, the following conclusions are presented:

- The use of steel pipe and expansive grout for anchoring CFRP bars was feasible for tensile testing but with limitations on bar tensile capacity. Further investigation is needed to develop anchor systems that have the capacity to transfer load high enough to bring large diameter and high strength CFRP bars to tensile failure.
- Failure mode is dependent on the preparation of the specimen, such as grout curing time, the diameter, length and wall thickness of anchor pipe, and properties of the bar, such as its strength, diameter and surface condition. Since almost every CFRP bar has its unique nature, it is difficult to test all specimens successfully with the same methodology even if the recommendation for FRP tensile testing is strictly followed.
- The test revealed the specimens had lower ultimate tensile strain and modulus of elasticity as compared to theoretical calculations. This could be attributed to low performance of raw materials or quality control problems.
- The S Series specimens had the largest strain and stiffness translation among all specimens, which indicated there is a good potential for the improvement of the proprietary bars made by different manufacturers.

The following conclusions were made for the bond test.

- The bond test can be used to give an indication of the bond strength between the FRP bars and epoxy, and also the epoxy and concrete.
- The role of the concrete strength is not well addressed by this test because the concrete block is in compression during the test, while in reality the concrete is in tension. A flexure type specimen may give a better indication of the role of the concrete strength.
- Longer bonded lengths perform better in this test because the failure is less likely to be due to concrete rupture.

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