AHTD TRC TRANSPORTATION RESEARCH COMMITTEE

TRC9305

# A Study of the Properties of Fiber Composite Bars for Use in Highway Bridge Deck Reinforcement

T. E. Cousins, L. G. Pleimann, J. J. Schemmel,
Mr. Faruqi, D. Mbekelu, J. Williams

Final Report

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Conducted by

Department of Civil Engineering
University of Arkansas
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and

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Auburn University
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In Cooperation With

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Report No. FHWA/AR-94-03

University of Arkansas
Fayetteville, Arkansas 72201

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## FINAL PROJECT SUMMARY REPORT

A study and evaluation of the basic properties of fiber reinforced polymer (FRP) rods for use as bridge deck reinforcement was completed in April, 1996. Two reinforcing fibers were studied, E-glass and carbon. The glass fiber (GFRP) bars tested were straight production line bars, using vinylester resin as the polymer matrix, manufactured by PolyStructures, Inc. of Little Rock, Arkansas. The data for GFRP bars using a polyester resin matrix were available for comparison from other tests done for the manufacturer under a separate contract. The carbon fiber (CFRP) bars were hand laid-up by Marshall-Vega Corporation of Marshall, Arkansas, using an epoxy matrix.

The study was conducted in two parts, tension tests and bond pull-out tests. The tension tests were done at the University of Arkansas. These tests were controlled at a constant stroke rate of 0.07 inches (0.178 cm)/minute in a 110 kip (439 kN) MTS test frame to failure. A secant modulus of elasticity between the points of 5% and 50% of ultimate strength was calculated for each bar. Also, fatigue tests were done by subjecting bars to repeated loads at one Hz at various percentages of the bar failure strength ranging between 10% and 50% for the GFRP bars and between 50% and 90% for the CFRP bars. These latter tests indicated a definite need for a reduction in applied stress to be able to achieve a larger number of repeated loadings.

The GFRP bars were consistent in their strength, averaging 70 ksi (483 MPa) ultimate stress for the #4 and #5 bars, and 95 ksi (655 MPa) for the #6 bars. The #4, #5, and #6 bars (#'s 13, 16, 19 bar sizes by new metric designation) showed average moduli of elasticity of 4.9, 5.3, and 6.0 million psi (33.8, 36.5, and 41.4 GPa)respectively. The results for the CFRP bars were more scattered because of the hand manufacturing process. The carbon bars showed an average ultimate tensile strength of 122.5, 125.7, and 107.2 ksi (844.6, 866.7, and 739.1 MPa) for the #4, #5, and #6 bars respectively. The #4, #5, and #6 bars showed average modulii of elasticity of 11.3, 12.2, and 10.9 million psi (77.9, 84.1, and 75.2 GPa) respectively.

The second part of the study was completed at Auburn University. Bond pull-out tests were made of each size of GFRP bar to determine the bond strength coefficient. The coefficient, k, varied with size of bar, having an average value of 19.88, 26.79, and 32.75 for glass reinforced #4, #5, and #6 bars respectively. This indicates the need for development lengths some 75%, 31%, and 7% greater than the current ACI Code formulation for individual steel rebars of the same respective "size." This tendency of increased bond capacity with increasing bar size is consistent with earlier tests done at the University of Arkansas on GFRP bars from a different manufacturer.

Because of the distortion and inconsistency of the outer shape of the carbon reinforced FRP bars there was excessive scatter in the bond results. It was decided to not continue with the bond strength tests of CFRP bars. However, it was felt that good bond strength consistent with that of GFRP bars will be available in the future from CFRP bars when they are machine made.

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## ACKNOWLEDGEMENTS

The research documented in this report has been funded by the U.S. Department of Transportation's Federal Highway Administration and the Arkansas Highway and Transportation Department.

The technical research team included Dr. Thomas E. Cousins of Auburn University, and Drs. John J. Schemmel, and Larry G. Pleimann of the University of Arkansas. All served as co-principal investigators. Liason with PolyStructures, Inc., a subsidiary of ETC Engineers, Inc. of Little Rock was Mr. Will Andrews. Mr. David Ratchford, President of Marshall-Vega Corporation of Marshall, Arkansas was of great help in trying times in getting the carbon fiber based rods ready.

Mrs. Jennifer Williams served as the principal graduate assistant on the project. Messrs. Davis Mbekelu and Mohammad Faruqi worked also on the project at various times. They were ably assisted by Mr. Mark Kuss and Miss Becky Collier in the operation of the MTS equipment.

The machine shop personnel of the Engineering Research Center were invaluable in making the specimen forms and the holding devices necessary for conducting the tension tests. Thanks go especially to Mr. Don Bell and Mr. Randal Springer for their energy and expertise.

# 1. BACKGROUND

## 1.1 Introduction

The increased use of deicer chemicals that began in the sixties has contributed greatly to the deterioration of reinforced concrete bridge decks and pavements in the United States. The infiltration of chloride ions into the concrete causes the pH surrounding the reinforcing steel to become acidic. This change in pH allows the steel to oxidize. The resulting iron oxide crystals expand as much as 16 times the volume of the source steel [Crumpton, 1985]. The internal expansion produces high tensile stresses in the concrete. This leads to cracking near the top surface and spalling of the concrete follows. The direct exposure of the underlying reinforcement to the environment and traffic loads hastens the deterioration of the slab. Unless the damaged area is repaired, a significant loss of strength and/or service life of a pavement or deck will occur.

Most efforts to control the corrosion of deformed deck and pavement reinforcement have been directed toward protection of the steel bars. Additional concrete cover, surface sealants for the concrete, corrosion inhibitors mixed with the concrete, reduced concrete permeability, cathodic protection, epoxy coating, and galvanizing are examples. The use of fusion epoxy coated bars has become standard in the effort to protect concrete reinforcing steel from corrosion. However, epoxy coating is not the final answer since small cracks in the coating may hasten local corrosion [Clear, 1992]. Epoxy coating is also being used with pavement dowel bars. Few other alternatives have been proposed for the protection of steel reinforcement apart from the suggestion of using more expensive stainless steel [Black, et al, 1988], or to search for another more effective coating.

An alternate effort has attempted the development of other forms of reinforcement that are not susceptible to corrosion. Fiber reinforced polymer (FRP) bars provide one such option. This "composite" material consists of thin high-strength synthetic fibers embedded within a hardened polymer matrix. FRP bars have already been used for slabs on grade, as prestressing tendons [Preis and Bell, 1987; Nanni, 1991], in marine environment structures, and in structures wherein non-magnetic properties are important such as magnetic resonance imaging installations [Roll, 1991], and large transformer foundation pads. The bars are not susceptible to corrosion and have high tensile strength.

The early use of composites was driven by a search for improvement in the strength-weight ratio of structural materials used in military aircraft. Much of this literature is proprietary and/or classified. However, the application of composite materials to civil engineering type structures goes back several decades and interest grows daily. Recent contributions to the growth of the basic literature include: 1) the ASCE Specialty Conference on "Advanced Composites in Civil Engineering Structures" held in Las Vegas, January 31 to February 1, 1991, 2) the recent industry-government-university consortium "Composites in Construction Workshop" at West Virginia University, in November, 1991, that tried to set priorities for FRP research and to form an organization for the promotion of composites in construction, 3) the establishment of ACI Committee 440 on "FRP Bar and Tendon Reinforcement," 4) the first international conference on "Advanced Composite Materials in Bridges and Structures," held in Sherbrooke, Quebec, Canada in 1992, 5) the ACI "International Symposium on FRP Reinforcement for Concrete Structures" held in Vancouver, British Columbia, Canada in March, 1993, and 6) the "First International Conference on Composites in Infrastructure," held in Tuscon, Arizona in January of 1996. At this writing the appropriate committee of ASTM is seeking to establish a standard D2018 for the testing of FRP composite bars. And in the meantime the literature available in the usual channels of communication is also rapidly increasing.

Interest in these types of materials at the University of Arkansas began over a decade ago. Tests previous to this study have examined a limited range of glass and KEVLAR-49 reinforced small-diameter bars in tensile strength, modulus of elasticity, and pull-out bond [Pleimann, 1991]. The results suggested that such materials are strong enough, can be made stiff enough, and have sufficient bond strength to substitute for steel reinforcement. However, many basic questions regarding the properties and behavior of the fiber reinforced bars are still unanswered and must be addressed before their widespread use becomes feasible. Similar results have been evaluated at other schools [Faza & GangaRao, 1990].

The current study is the attempt to establish baseline data regarding the tensile strength, modulus of elasticity, and bond strength in Portland cement concrete of several types of FRP deformed bars manufactured by Arkansas enterprises. The study included work with glass fiber reinforced vinylester matrix rods (GFPR) made by PolyStructures, Inc., a subsidiary of ETC Engineers, Inc. of Little Rock, Arkansas, and carbon fiber reinforced epoxy matrix rods (CFRP) manufactured by Marshall-Vega Corporation of Marshall, Arkansas. In addition to static tests, it was initially intended that the bars be subjected to repeated tensile load ranging between zero and 50 percent of their ultimate tensile strength for 500,000 cycles so as to investigate any reduction in tensile strength from fatigue loss. As will be described later this objective was modified because of results received. This final report describes the testing procedures and results received in this effort.

## 1.2 Research Objectives

The research objectives of this study consisted of:

1. The evaluation of the following static physical properties of standard sizes of deformed-surface fiber reinforced polymer rods using two types of fibers:

    a. The failure strength, and ultimate tensile stress capacity.

    b. The average modulus of elasticity.

    c. The bond strength coefficient of the rods in Portland cement concrete.

2. An initial evaluation of the residual tensile strength of these same bars after repeated tensile loading between essentially zero load and 50% of their static tensile strength.

## 1.3 Scope of the Study

Sixteen glass FRP specimens for strength tests and twelve specimens for bond tests were obtained in each of three bars sizes, #4's, #5's and #6's (#13's, #16's and #19's in "soft metric" designation, hereinafter "m"). These specimens represented normal production examples of FRP rods with a vinylester matrix and E-glass fiber reinforcement in the order of 70% by volume, as manufactured by PolyStructures, Inc. of Little Rock, Arkansas. Strength tests of #6 (#19m) bars made for a PolyStructures client were done to examine consistency of manufacture between lots. Also, similar bars with a polyester matrix were tensile tested for comparison.

A small group of fifteen GFRP polyester matrix specimens were also tensile tested in groups of three at varying rates of loading to determine to what extent that variable would effect the results of static tensile testing. The force/deformation curves for these materials is non-ductile and could be effected by the head-speed of the testing machine.

Sixteen carbon FRP specimens for strength tests were obtained in each of three bars sizes, #4's (#13m's), #5's (#16m's) and #6's (#19m's). An initial shipment of six #5's (#16m's) was sent to Auburn University for bond tests. These specimens were all "hand-laid-up" CFRP rods with an epoxy matrix made by Marshall-Vega, Inc. of Marshall, Arkansas. The use of an epoxy matrix was a result of the "mind-set" of engineers both at Marshall-Vega and at PolyStructures, Inc., the company that manufactured the GFRP rebars whose testing was reported in the first interim report.

A common use of carbon fibers in the past was in the form of flat sheets for the aircraft industry. The sheets were kept at low temperatures to retard the hardening of the epoxy. Once shipped to the user they were stamped to the desired shape and heated. Most persons familiar with carbon fiber composites were of the opinion that epoxy was the only compatible polymer for carbon fibers. It was later learned that vinylesters do exist compatible with carbon fiber. In the meantime, the existing hand-made specimens were tested. It is hoped that future tests may be made of carbon fiber rebars made by pultrusion using a compatible vinylester.

# 2. TESTING PROGRAM

## 2.1 Tension Testing

Static tensile testing of the FRP rebars was done with a 110 kip (489 kN) capacity MTS universal testing machine. The machine is controlled by electronic feedback from measured load, strain, or stroke to a wide range of testing programs. The machine is located in the Civil Engineering laboratories of the Bell Engineering Center at the University of Arkansas.

All tensile specimens were gripped by means of devices mounted in the MTS machine containing a tapered hole varying from 1.25 inches (3.175 cm) diameter to 5.00 inches (12.70 cm) diameter over a longitudinal length of 24 inches (60.96 cm). The holding devices were made of 6061-T6 aluminum in two symmetrical parts. They were connected together with class 8 machine bolts. The design ensured being able to reach a full 110 kips (489 kN) load. Two separate sets of three molds were made of the same material and mounted on two wood and plywood frames.

Tension specimens measuring 5'-1" (1.55 m) were placed in the molds and a corresponding tapered segment of high-strength grout was cast on one end of the specimen with an approximate 0.5 inches (1.27 cm) of rod extending beyond the grouted end. After a minimum of twelve hours curing, the specimen was removed from the form, rotated, the first end was wrapped in plastic film, and the opposite end was cast. This left an exposed 12" (30.5 cm) length of rod between the two ends for the easy attachment of an extensometer with an 8" (20.3 cm) gage length. The most recently cast end was allowed to cure in the molds for at least two days. When the specimen was removed from the form the second end was wrapped in plastic film also until the tensile test was performed. Care was taken to avoid curvature of the rods during casting, and in transporting the specimens from the casting site to the testing facility.

### 2.1.1 Direct Tension Tests

After curing, the specimens were mounted in the similarly shaped holding device in the 110 kip (498 kN) capacity MTS universal testing machine. Control of the loading procedure consisted of limiting the actuator movement ("stroke") to a constant rate of 0.07 inches (0.178 cm) per minute. This head speed was randomly chosen. It has since been learned that the proposed ASTM D2018 standard will use a head speed of 0.05 inches (0.127 cm) per minute. Fifteen additional GFRP tests were done in groups of three at five head speeds ranging between 0.05 and 0.5 inches (0.127 and 1.27 cm) per minute. No significant differences were found in the results. Electronic readings in millivolts from the stroke, the extensometer extension, and the load cell were collected on a computer hard disk for later transfer to a spread sheet program for analysis and plotting.

In addition to noting the maximum force obtained from each rod, the load and deformation at 5% and 50% of the maximum force were obtained and a secant modulus of elasticity evaluated from the data.

### 2.1.2 Fatigue Tests

The original intent of the fatigue testing was described in the final revision of the proposal for this project. It was to subject six bars of each bar size for each of the two fiber materials to a repeated load varying between essentially zero and 50% of the average ultimate strength of the bars that had been evaluated by the previous static tension tests. This loading was to be continued for 500,000 cycles. Then the bar would be failed with a static tension test to evaluate any reduction of capacity due to the previous repeated loading.

The initial intent was to operate the repeated load at either 6 Hz (modeling two axles about 14 ft. (4.27 m) apart traveling at approximately 65 mph (104.6 kph)) or 24 Hz (modeling dual-wheel axles passing at 65 mph (104.6 kph)). However, the capacity of the hydraulic pump, and the large loads involved restricted the frequency to 1 Hz. The fatigue loading of the first #4 (#13 metric) GFRP specimen was begun and it was expected that the test would take approximately 5-3/4 days to complete. However, returning to the lab several hours later the writer found that the specimen had already failed.

The testing procedure was changed. The GFRP bars were fatigue tested to failure under repetitive loads varying from zero to a specific percentage of their ultimate tensile load. The percentage used started at roughly 50% and in subsequent tests varied in negative increments of 10% down to a final load level of 10%. The number of cycles completed before failure were recorded. When the number of cycles that the bar had resisted exceeded 500,000 the testing procedure was stopped and the final count noted.

When fatigue testing of CFRP bars was begun it was assumed that the same revised procedure would be used. The first CFRP tests were begun at 50% of the tensile strength. It was expected that this loading would lead to a quick failure. But it did not. Instead, the initial CFRP test at 50% of the static load capacity of the carbon fiber bar exceeded 500,000 cycles. This was the initial indication of the superior fatigue strength of the carbon fiber bars by comparison to the glass fiber bars. The percentage of ultimate tensile load for the CFRP bars was changed to a 50% to 90% range which proved appropriate to that material.

## 2.2 Testing for Bond Strength

The intent at Auburn University was to test twelve specimens in bond pull-out resistance for each bar size. The twelve would all be tested in four groups of three specimens, each group at a different embedment length in the concrete. It was also intended to use a concrete strength of 4000 psi (27.58 MPa) for all specimens corresponding to AHTD specified Class S(AE). Difficulties associated with the casting process and other matters resulted in changes from the intended plan. The specimen ends were cast in 8 inch (20.32 cm) square cross-section blocks with varying embedment lengths. The specimens were cast at two different times using two different batches that resulted in average concrete strengths of 3050 psi (21.03 MPa) and 2500 psi (17.24 MPa). These differences were taken into account in evaluating the bond test results. Also, for each of the bar sizes three steel bar specimens were also cast and some tested for comparison.

The bars were pulled until slip was noted at the free end of the embedment. The tension exerted that caused the slip was recorded. The results of these bond tests of the full range of GFRP bars is indicated below.

An initial shipment of six #5 (#16m) carbon FRP bars was sent to Auburn University as the "hand-lay-up" procedure was optimized. Despite the best effort at hand manufacture the outer surface of these bars was so rough and irregular the attempts at bond testing proved highly inconsistent. The hope of getting usable bond test data was abandoned until a method could be found to manufacture the bars by the usual pultrusion process.

# 3. TEST RESULTS

## 3.1 Tension Testing

The results of both the static tensile strength and the modulus of elasticity testing for both the glass and carbon FRP bars is given in tabular form below, and the results are combined in graphic presentation. The interpretation and application of the results follow in Section 4.

### 3.1.1 Static Strength and Modulus of Elasticity Results

Glass Fiber Reinforced Bars

Table 1 gives the results of the six tensile tests done for each of the three GFRP bar sizes. The results include the ultimate force capacity, the ultimate stress capacity, and the modulus of elasticity. The stress value is based on an assumed cross sectional area equivalent to that of a steel bar of the same "size" number. For each bar size, the averages are given for each of the three results, together with the corresponding standard deviation, and the coefficient of variation. The coefficients of variation are small and decrease with increasing bar size. The coefficient of variation for typical Portland cement concrete results would be in the order of 0.15. The manufacture of the bars give quite consistent results.

Tables 2A and 2B show the results from two batches of #6 (#19 metric) GFRP bars made by Poly-Structures and tested by the department for one of their clients. The results are very close to the values received from testing of the GFRP #6's supplied for the project. Table 3 shows results of recent testing done by the department of GFRP bars with a polyester matrix. Vinylester is the more commonly used polymer for GFRP bars, but it is more expensive than polyester. Polyester is preferable only in dry climates. The results for the #'s 5 (#16m) and

6 (#19m) bars are essentially the same as for the same size vinylester matrix bars. However, the #4 (#13m) polyester bars were some 28% stronger than the corresponding vinylester matrix bars.

Table 4 shows the results of tests of fifteen #6 polyester matrix GFRP bars tension tested at different head speeds. Figure 1 is a plot of those results. A general trend of increased strength and stiffness with faster head speed is observed. It should be noted that the specimens using the 0.07 inches (0.178 cm)/minute head speed are from a different batch. In any case, the overall difference caused by varying the head speed seems small. This problem will be eliminated by the standard of 0.05"(0.127 cm)/min. head speed of the proposed ASTM D2018.

Carbon Fiber Reinforced Bars

Table 5 gives the results of the five or six successful tensile tests done for each of the three bar sizes. The results include the ultimate force capacity, the ultimate stress capacity, and the modulus of elasticity. The stress value is based on an assumed cross sectional area equivalent to that of a steel bar of the same "size" number. For each bar size, the averages are given for each of the three results, together with the corresponding standard deviation, and the coefficient of variation. The coefficient of variation for typical Portland cement concrete results would be in the order of 0.15. The CFRP bars give results that are, for the most part, commensurate with this standard of consistency despite the imprecise method of manufacture.

Figure 2 summarizes and combines the tension test results for both the GFRP and CFRP rebars. Different symbols are used for different sized bars. The tightly compacted data to the lower left left-hand of the plot are GFRP results. The compactness demonstrates the consistency achieved by the mechanical pultrusion process. The more scattered data to the upper right-hand of the plot are the CFRP results. The scatter shows the inconsistency inherent in the hand manufacturing procedure.

## Table 1 Tension Test Results for GFRP Vinylester Matrix Bars

| Specimen Number | Rebar Size Number (steel) | Ultimate Force (kips) | Ultimate Stress (ksi) | Modulus of Elasticity (ksi) |
|---|---|---|---|---|
| G4A | 4 | 3.418 | 17.090* | 4,368.348 |
| G4B | 4 | 13.721 | 68.605 | 4,995.753 |
| G4C | 4 | 15.039 | 75.195 | 5,643.645 |
| G4I | 4 | 12.256 | 61.280 | 4,640.205 |
| G4J | 4 | 14.063 | 70.315 | 5,523.652 |
| G4K | 4 | 13.232 | 66.160 | 4,130.921 |
| **Average** | **4** | **13.662** | **68.311** | **4,883.754** |
| **Std.Dev.** | | | **5.137** | **615.006** |
| **Coef./Var.** | | | **0.075** | **0.126** |
| G5A | 5 | 21.973 | 70.881 | 5,014.226 |
| G5B | 5 | 18.994 | 61.271 | 5,466.098 |
| G5C | 5 | 23.193 | 74.816 | 5,076.120 |
| G5D | 5 | 22.705 | 73.242 | 5,448.549 |
| G5E | 5 | 21.387 | 68.990 | 5,530.090 |
| G5F | 5 | 22.998 | 74.187 | 5,257.944 |
| **Average** | **5** | **21.875** | **70.565** | **5,298.838** |
| **Std.Dev.** | | | **5.046** | **217.323** |
| **Coef/Var.** | | | **0.072** | **0.041** |
| G6A | 6 | 42.627 | 96.879 | 5,923.138 |
| G6C | 6 | 41.797 | 94.993 | 6,020.103 |
| G6D | 6 | 44.043 | 100.098 | 6,080.383 |
| G6E | 6 | 43.555 | 98.989 | 6,190.997 |
| G6F | 6 | 40.332 | 91.664 | 5,933.043 |
| G6G | 6 | 41.797 | 94.993 | 5,835.606 |
| **Average** | **6** | **42.359** | **96.270** | **5,997.212** |
| **Std.Dev.** | | | **3.062** | **127.055** |
| **Coef./Var.** | | | **0.032** | **0.021** |

* not used in calculating average

## Table 1m Tension Test Results for GFRP Vinylester Matrix Bars

| Specimen Number | Metric Rebar Size (steel) | Ultimate Force (kN) | Ultimate Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|---|---|
| G4A | 13 | 15.204 | 117.831* | 30,118.70 |
| G4B | 13 | 61.034 | 473.015 | 34,444.50 |
| G4C | 13 | 66.897 | 518.451 | 38,911.56 |
| G4I | 13 | 54.517 | 422.511 | 31,993.09 |
| G4J | 13 | 62.555 | 484.805 | 38,084.24 |
| G4K | 13 | 58.859 | 456.157 | 28,481.70 |
| **Average** | **13** | **60.772** | **470.988** | **33,672.30** |
| **Std.Dev.** | | | **35.418** | **4,240.32** |
| **Coef./Var.** | | | **0.075** | **0.126** |
| G5A | 16 | 97.741 | 488.707 | 34,571.87 |
| G5B | 16 | 84.494 | 422.449 | 37,687.42 |
| G5C | 16 | 103.168 | 515.838 | 34,998.61 |
| G5D | 16 | 100.997 | 504.986 | 37,566.42 |
| G5E | 16 | 95.134 | 475.669 | 38,335.47 |
| G5F | 16 | 102.300 | 511.501 | 36,252.25 |
| **Average** | **16** | **97.305** | **486.529** | **36,534.20** |
| **Std.Dev.** | | | **34.791** | **1,498.39** |
| **Coef/Var.** | | | **0.072** | **0.041** |
| G6A | 19 | 189.654 | 667.957 | 40,838.60 |
| G6C | 19 | 185.922 | 654.954 | 41,507.15 |
| G6D | 19 | 195.913 | 690.151 | 41,922.76 |
| G6E | 19 | 193.742 | 682.505 | 42,685.42 |
| G6F | 19 | 179.406 | 632.001 | 40,906.89 |
| G6G | 19 | 185.922 | 654.954 | 40,235.09 |
| **Average** | **19** | **188.422** | **663.758** | **41,349.32** |
| **Std.Dev.** | | | **21.112** | **876.015** |
| **Coef./Var.** | | | **0.032** | **0.021** |

* not used in calculating average

**Table 2A Results Of Tests of Separate Batch #1 of #6 Vinylester Matrix GFRP Bars**

| Specimen Number | Ultimate Force (kips) | Ultimate Stress (ksi) | Modulus of Elasticity (ksi) |
|---|---|---|---|
| I6-1 | 43.040 | 97.818 | 5,789.453 |
| I6-2 | 42.700 | 97.045 | 6,247.710 |
| I6-3 | 41.250 | 93.750 | 5,947.717 |
| I6-4 | 42.700 | 97.045 | 6,269.634 |
| I6-5 | 41.720 | 94.818 | 6,377.049 |
| **Average** | **42.280** | **96.091** | **6,126.313** |
| **Std.Dev.** | **0.759** | | **246.738** |
| **Coef./Var.** | **0.018** | | **0.040** |

**Table 2B Results of Tests of Separate Batch #2 of #6 Vinylester Matrix GFRP Bars**

| Specimen Number | Ultimate Force (kips) | Ultimate Stress (ksi) | Modulus of Elasticity (ksi) |
|---|---|---|---|
| I6-6 | 43.530 | 98.932 | 6,070.416 |
| I6-7 | 39.710 | 90.250 | 5,189.904 |
| I6-8 | 44.400 | 100.909 | 6,084.878 |
| I6-9 | 40.460 | 91.955 | 5,774.652 |
| I6-10 | 42.170 | 95.841 | 5,796.640 |
| I6-11 | 42.570 | 96.750 | 5,248.463 |
| **Average** | **42.140** | **95.773** | **5,694.159** |
| **Std.Dev.** | **1.786** | | **390.930** |
| **Coef./Var.** | **0.042** | | **0.069** |

Table 2Am Results Of Tests of Separate Batch #1 of #19 Vinylester Matrix GFRP Bars

| Specimen Number | Ultimate Force (kN) | Ultimate Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|---|
| I6-1 | 191.451 | 674.431 | 39,916.87 |
| I6-2 | 189.939 | 669.102 | 43,076.44 |
| I6-3 | 183.489 | 646.383 | 41,008.06 |
| I6-4 | 189.939 | 669.102 | 43,227.60 |
| I6-5 | 185.580 | 653.747 | 43,968.20 |
| **Average** | **188.071** | **662.529** | **42,239.44** |
| **Std.Dev.** | **3.376** | | **1,701.20** |
| **Coef./Var.** | **0.018** | | **0.040** |

Table 2Bm Results of Tests of Separate Batch #2 of #19 Vinylester Matrix GFRP Bars

| Specimen Number | Ultimate Force (kN) | Ultimate Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|---|
| I6-6 | 193.631 | 682.112 | 41,854.04 |
| I6-7 | 176.639 | 622.252 | 35,783.13 |
| I6-8 | 197.501 | 695.743 | 41,953.76 |
| I6-9 | 179.975 | 634.007 | 39,814.82 |
| I6-10 | 187.581 | 660.800 | 39,966.42 |
| I6-11 | 189.361 | 667.068 | 36,186.88 |
| **Average** | **187.448** | **660.332** | **39,259.84** |
| **Std.Dev.** | **7.945** | | **2,695.37** |
| **Coef./Var.** | **0.042** | | **0.069** |

**Table 3 Tension Test Results of Polyester Matrix GFRP Bars**

| Specimen Number | Rebar Size Number (steel) | Ultimate Force (kips) | Ultimate Stress (ksi) | Modulus of Elasticity (ksi) |
|---|---|---|---|---|
| P4-A | 4 | 18.560 | 92.800 | 4,915.425 |
| P4-B | 4 | 18.650 | 93.250 | 5,321.293 |
| P4-C | 4 | 16.720 | 83.600 | 5,100.325 |
| P4-D | 4 | 16.320 | 81.600 | 5,122.138 |
| P4-E | 4 | 17.285 | 86.425 | 5,157.804 |
| **Average** | **4** | **17.507** | **87.535** | **5,123.397** |
| **Std.Dev.** | | **1.060** | **5.299** | **145.028** |
| **Coef./Var.** | | | **0.061** | **0.028** |
| P5-A | 5 | 20.800 | 67.097 | 4,672.288 |
| P5-B | 5 | 21.240 | 68.516 | 4,139.635 |
| P5-C | 5 | 22.850 | 73.710 | N/A** |
| P5-D | 5 | 21.580 | 69.613 | 4,259.746 |
| P5-E | 5 | 21.045 | 67.887 | 6,327.288*** |
| **Average** | **5** | **21.503** | **69.365** | **4,849.789** |
| **Std.Dev.** | | **0.805** | **2.597** | **1,011.101** |
| **Coef/Var.** | | | **0.037** | **0.208** |
| P6-A | 6 | 36.230 | 82.341 | 4,875.905 |
| P6-B | 6 | 38.720 | 88.000 | 4,869.897 |
| P6-C | 6 | 42.970 | 97.659 | 6,108.980*** |
| P6-D | 6 | 36.230 | 82.341 | 4,887.880 |
| P6-E | 6 | 25.293* | 63.233* | 4,815.064 |
| **Average** | **6** | **38.538** | **87.585** | **5,111.545** |
| **Std.Dev.** | | **3.180** | **7.226** | **558.284** |
| **Coef./Var.** | | | **0.083** | **0.109** |

* not used in calculating averages, etc.
** not available; strain was not recorded
*** this excessive value increased the coefficient of variation

**Table 3m Tension Test Results of Polyester Matrix GFRP Bars**

| Specimen Number | Metric Rebar Size (steel) | Ultimate Force (kN) | Ultimate Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|---|---|
| P4-A | 13 | 82.559 | 639.830 | 33,890.66 |
| P4-B | 13 | 82.959 | 642.940 | 36,689.02 |
| P4-C | 13 | 74.374 | 576.402 | 35,165.50 |
| P4-D | 13 | 72.595 | 562.612 | 35,315.90 |
| P4-E | 13 | 76.887 | 595.879 | 35,561.81 |
| **Average** | **13** | **77.875** | **603.533** | **35,324.58** |
| **Std.Dev.** | | **4.715** | **36.535** | **999.93** |
| **Coef./Var.** | | | **0.061** | **0.028** |
| P5-A | 16 | 92.523 | 462.618 | 32,214.29 |
| P5-B | 16 | 94.480 | 472.401 | 28,541.78 |
| P5-C | 16 | 101.642 | 508.213 | N/A** |
| P5-D | 16 | 95.993 | 479.965 | 29,369.91 |
| P5-E | 16 | 93.613 | 468.064 | 43,625.11*** |
| **Average** | **16** | **95.650** | **478.255** | **33,438.12** |
| **Std.Dev.** | | **3.581** | **17.906** | **6,971.30** |
| **Coef/Var.** | | | **0.037** | **0.208** |
| P6-A | 19 | 161.159 | 567.721 | 33,618.18 |
| P6-B | 19 | 172.235 | 606.739 | 33,576.76 |
| P6-C | 19 | 191.140 | 673.335 | 42,119.93*** |
| P6-D | 19 | 161.159 | 567.721 | 33,700.74 |
| P6-E | 19 | 112.509* | 435.976* | 33,198.70 |
| **Average** | **19** | **171.426** | **603.877** | **35,242.86** |
| **Std.Dev.** | | **14.145** | **49.822** | **3,849.23** |
| **Coef./Var.** | | | **0.083** | **0.109** |

* not used in calculating averages, etc.
** not available; strain was not recorded
*** this excessive value increased the coefficient of variation

**Table 4m Results Of Tests of #13 Polyester Matrix GFRP Bars Under Varying Loading Rates**

| Loading Rate (cm/min) | Specimen Number | Ultimate Force (kN) | Ultimate Stress (MPa) |
|---|---|---|---|
| **0.127** | P4-7 | 72.977 | 565.577 |
| | P4-8 | 69.503 | 538.653 |
| | P4-12 | 73.849 | 572.354 |
| | **Average** | **72.110** | **558.855** |
| **0.178** | P4-A | 82.159 | 636.731 |
| | P4-B | 83.004 | 643.281 |
| | P4-C | 74.374 | 576.402 |
| | **Average** | **79.846** | **618.804** |
| **0.254** | P4-16 | 83.622 | 648.073 |
| | P4-20 | 72.977 | 565.577 |
| | P4-21 | 79.494 | 616.081 |
| | **Average** | **78.698** | **624.493** |
| **0.508** | P4-11 | 81.015 | 627.811 |
| | P4-13 | 81.665 | 632.904 |
| | P4-15 | 79.058 | 612.703 |
| | **Average** | **80.580** | **624.493** |
| **0.762** | P4-4 | 74.063 | 573.989 |
| | P4-9 | 81.451 | 631.249 |
| | P4-10 | 77.355 | 599.499 |
| | **Average** | **77.621** | **601.581** |
| **1.270** | P4-5 | 87.314 | 676.686 |
| | P4-6 | 79.712 | 617.770 |
| | P4-14 | 78.627 | 609.359 |
| | **Average** | **81.883** | **634.607** |

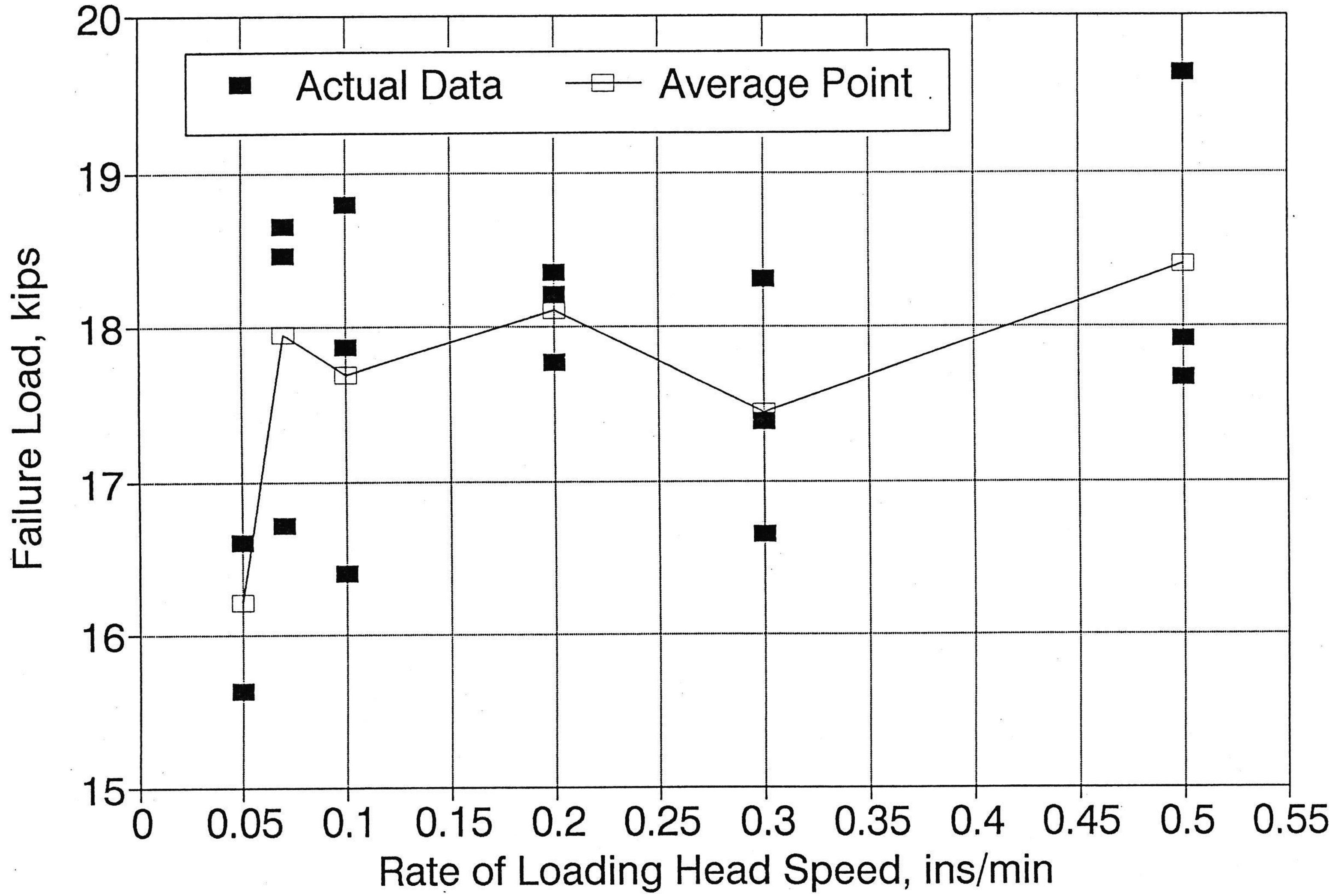


**Figure 1: Effect of Loading Rate on Tensile Failure Load**

**Table 5 Tension Test Results for Carbon Fiber Epoxy Matrix Bars**

| Specimen Number | Rebar Size Number (steel) | Ultimate Force (kips) | Ultimate Stress (ksi) | Modulus of Elasticity (ksi) |
|---|---|---|---|---|
| C4-1 | 4 | ng | ng | ng |
| C4-2 | 4 | 24.658 | 123.290 | 11,598.28 |
| C4-3 | 4 | 26.318 | 131.590 | 11,659.54 |
| C4-4 | 4 | 27.637 | 138.185 | 11,549.35 |
| C4-5 | 4 | 22.949 | 114.745 | 10,999.81 |
| C4-6 | 4 | 21.000 | 105.000 | 10,927.50 |
| **Average** | **4** | **24.512** | **122.562** | **11,346.90** |
| **Std.Dev.** | | | **13.188** | **352.95** |
| **Coef./Var.** | | | **0.108** | **0.031** |
| C5-1 | 5 | ng | ng | ng |
| C5-2 | 5 | 54.883 | 177.042 | 15,290.66 |
| C5-3 | 5 | 32.861 | 106.003 | 10,586.46 |
| C5-4 | 5 | 30.957 | 99.861 | 10,466.43 |
| C5-5 | 5 | 37.012 | 119.394 | 12,537.14 |
| C5-6 | 5 | 39.111 | 126.165 | 12,035.27 |
| **Average** | **5** | **38.965** | **125.693** | **12,183.19** |
| **Std.Dev.** | | | **30.543** | **1,955.78** |
| **Coef/Var.** | | | **0.243** | **0.161** |
| C6-1 | 6 | 51.221 | 116.411 | 10,448.79 |
| C6-2 | 6 | 46.973 | 106.757 | 10,517.76 |
| C6-3 | 6 | 46.631 | 105.980 | 10,773.96 |
| C6-4 | 6 | 57.520 | 130.727 | 12,652.99 |
| C6-5 | 6 | 39.160 | 89.000 | 8,177.41 |
| C6-6 | 6 | 41.406 | 94.105 | 11,890.88 |
| **Average** | **6** | **47.152** | **107.163** | **10,743.63** |
| **Std.Dev.** | | | **15.118** | **1,528.80** |
| **Coef./Var.** | | | **0.141** | **0.142** |

**Table 5m Tension Test Results for Carbon Fiber Epoxy Matrix Bars**

| Specimen Number | Metric Rebar Size (steel) | Ultimate Force (kN) | Ultimate Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|---|---|
| C4-1 | 13 | ng | ng | ng |
| C4-2 | 13 | 109.684 | 850.055 | 79,967.32 |
| C4-3 | 13 | 117.068 | 907.281 | 80,389.70 |
| C4-4 | 13 | 122.935 | 952.752 | 79,629.96 |
| C4-5 | 13 | 102.082 | 791.139 | 75,841.02 |
| C4-6 | 13 | 93.413 | 723.949 | 75,342.46 |
| **Average** | **13** | **109.035** | **845.035** | **78,234.12** |
| **Std.Dev.** | | | **90.928** | **2,433.50** |
| **Coef./Var.** | | | **0.108** | **0.031** |
| C5-1 | 16 | ng | ng | ng |
| C5-2 | 16 | 244.132 | 1,220.662 | 105,425.39 |
| C5-3 | 16 | 146.173 | 730.865 | 72,991.07 |
| C5-4 | 16 | 137.704 | 688.517 | 72,163.49 |
| C5-5 | 16 | 164.638 | 823.193 | 86,440.53 |
| C5-6 | 16 | 173.974 | 869.877 | 82,980.26 |
| **Average** | **16** | **173.325** | **866.623** | **84,000.13** |
| **Std.Dev.** | | | **210.587** | **13,484.63** |
| **Coef/Var.** | | | **0.243** | **0.161** |
| C6-1 | 19 | 227.842 | 802.626 | 72,041.87 |
| C6-2 | 19 | 208.946 | 736.064 | 72,517.40 |
| C6-3 | 19 | 207.425 | 730.706 | 74,283.84 |
| C6-4 | 19 | 255.862 | 901.331 | 87,239.29 |
| C6-5 | 19 | 174.192 | 613.633 | 56,381.25 |
| C6-6 | 19 | 184.183 | 648.831 | 81,984.73 |
| **Average** | **19** | **209.298** | **738.863** | **74,074.72** |
| **Std.Dev.** | | | **104.235** | **10,540.70** |
| **Coef./Var.** | | | **0.141** | **0.142** |

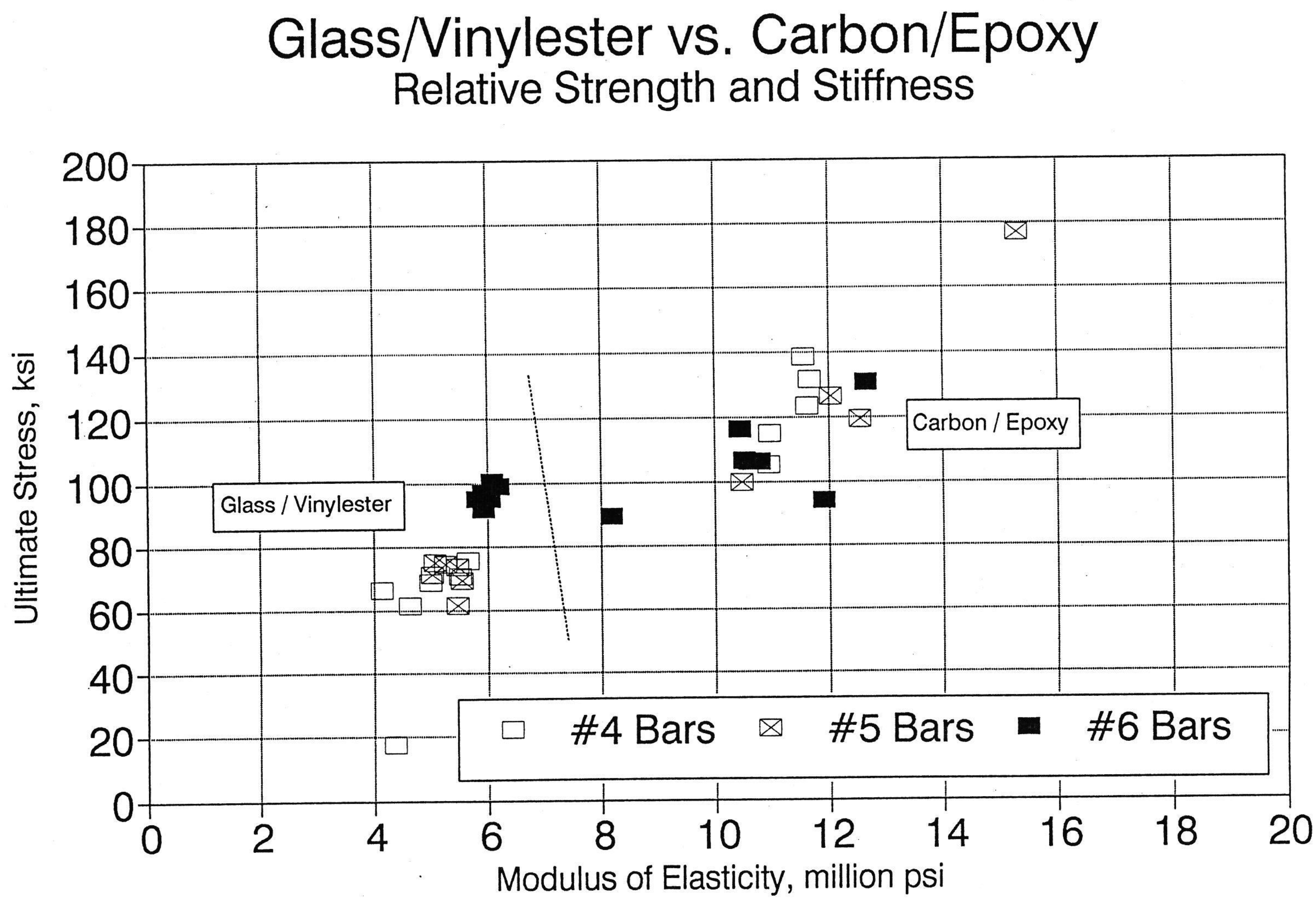


**Figure 2 Comparison of Relative Strength and Stiffness of Carbon and Glass Fiber Rebars**

### 3.1.2 Fatigue Testing Results

The results of the fatigue testing of both the glass and carbon FRP bars is given in tabular form below, and the results are combined in graphic presentation. The interpretation and application of the results follow in Section 4.

Glass Fiber and Carbon Fiber Reinforced Bars

Table 6 lists the results of this testing procedure for the glass reinforced rebars. Table 7 shows the results for the carbon reinforced rebars. Figures 3 and 4 show those results in two semi-log plots. In Figure 3 the vertical axis is the maximum stress level of the repeated load in ksi. In Figure 4 the vertical axis is the percent of the ultimate tensile load for each of the individual bar sizes. In both figures the horizontal axis is a logrithmic scale of the number of repetitions of load to failure. In both figures different symbols are used to indicate the results for different bar sizes.

Both plots describe a fatigue behavior consistent with that of a brittle material. They show an essentially linear decrease (on the semi-log plot) of strength versus number of repetitions of load. In most materials subject to fatigue strength reduction this plot is known as an S-N diagram (S=stress, N=number). Such plots will usually indicate also a lower limit of fatigue strength reduction associated with a stress level below which the repetitions of load can theoretically continue to an infinite number without causing a failure to the material. This level of stress is called an "endurance limit." The number of tests available for the GFRP and CFRP bars was insufficient to indicate a definite endurance limit. Also, the one variable examined, % of ultimate load, is insufficient to evaluate the true fatigue strength characteristics of these bars. Further, other frequencies of load repetition should be examined beyond 1Hz.

## TABLE 6 Results of Fatigue Loading of Glass Fiber Rebars @ 1Hz

| Specimen Number | Maximum Force Applied (kips) | Equivalent Steel Bar Area (sq.in.) | Maximum Stress Applied (ksi) | Percent of Average Ultimate Load | Number of Cycles Before Failure |
|---|---|---|---|---|---|
| G4D | 10 | 0.20 | 50.000 | 71.429 | 617 |
| G4NB | 10 | 0.20 | 50.000 | 71.429 | 219 |
| G4E | 8 | 0.20 | 40.000 | 57.143 | 324 |
| G4F | 8 | 0.20 | 40.000 | 57.143 | 1,237 |
| G4MB | 8 | 0.20 | 40.000 | 57.143 | 606 |
| G4G | 6 | 0.20 | 30.000 | 42.857 | 4,589 |
| G4NA | 6 | 0.20 | 30.000 | 42.857 | 39,650 |
| G4H | 4 | 0.20 | 20.000 | 28.571 | 104,655 |
| G4L | 4 | 0.20 | 20.000 | 28.571 | 18,470 |
| G4MA | 4 | 0.20 | 20.000 | 28.571 | 39,848 |
| G5K | 14 | 0.31 | 45.161 | 64.516 | 292 |
| G5M | 14 | 0.31 | 45.161 | 64.516 | 362 |
| G5I | 11 | 0.31 | 35.484 | 50.691 | 835 |
| G5J | 11 | 0.31 | 35.484 | 50.691 | 953 |
| G5G | 8 | 0.31 | 25.806 | 36.866 | 4,819 |
| G5H | 8 | 0.31 | 25.806 | 36.866 | 6,799 |
| G5L | 5 | 0.31 | 16.129 | 23.041 | 190,150 |
| G5N | 5 | 0.31 | 16.129 | 23.041 | 136,268 |
| G5O | 3 | 0.31 | 9.677 | 13.825 | 604,915* |
| G5P | 3 | 0.31 | 9.677 | 13.825 | 691,175* |
| G6H | 18 | 0.44 | 40.909 | 42.494 | 4,118 |
| G6P | 18 | 0.44 | 40.909 | 42.494 | 3,318 |
| G6I | 13 | 0.44 | 29.545 | 30.690 | 18,481 |
| G6O | 13 | 0.44 | 29.545 | 30.690 | 13,546 |
| G6N | 11 | 0.44 | 25.000 | 25.969 | 35,417 |
| G6J | 9 | 0.44 | 20.455 | 21.247 | 82,288 |
| G6M | 9 | 0.44 | 20.455 | 21.247 | 101,047 |
| G6K | 7 | 0.44 | 15.909 | 16.525 | 280,649 |
| G6L | 7 | 0.44 | 15.909 | 16.525 | 478,093 |

* test stopped before failure after more than 500,000 cycles

TABLE 6m Results of Fatigue Loading of Glass Fiber Rebars @ 1Hz

| Specimen Number | Maximum Force Applied (kN) | Equivalent Steel Bar Area (sq.mm) | Maximum Stress Applied (MPa) | Percent of Average Ultimate Load | Number of Cycles Before Failure |
|---|---|---|---|---|---|
| G4D | 44.5 | 129 | 344.74 | 71.429 | 617 |
| G4NB | 44.5 | 129 | 344.74 | 71.429 | 219 |
| G4E | 35.6 | 129 | 275.79 | 57.143 | 324 |
| G4F | 35.6 | 129 | 275.79 | 57.143 | 1,237 |
| G4MB | 35.6 | 129 | 275.79 | 57.143 | 606 |
| G4G | 26.7 | 129 | 275.79 | 42.857 | 4,589 |
| G4NA | 26.7 | 129 | 206.84 | 42.857 | 39,650 |
| G4H | 17.8 | 129 | 139.90 | 28.571 | 104,655 |
| G4L | 17.8 | 129 | 139.90 | 28.571 | 18,470 |
| G4MA | 17.8 | 129 | 139.90 | 28.571 | 39,848 |
| G5K | 62.3 | 199 | 311.37 | 64.516 | 292 |
| G5M | 62.3 | 199 | 311.37 | 64.516 | 362 |
| G5I | 48.9 | 199 | 311.37 | 50.691 | 835 |
| G5J | 48.9 | 199 | 244.65 | 50.691 | 953 |
| G5G | 35.6 | 199 | 244.65 | 36.866 | 4,819 |
| G5H | 35.6 | 199 | 177.93 | 36.866 | 6,799 |
| G5L | 22.2 | 199 | 111.21 | 23.041 | 190,150 |
| G5N | 22.2 | 199 | 111.21 | 23.041 | 136,268 |
| G5O | 13.3 | 199 | 66.72 | 13.825 | 604,915* |
| G5P | 13.3 | 199 | 66.72 | 13.825 | 691,175* |
| G6H | 80.1 | 284 | 282.06 | 42.494 | 4,118 |
| G6P | 80.1 | 284 | 282.06 | 42.494 | 3,318 |
| G6I | 57.8 | 284 | 203.71 | 30.690 | 18,481 |
| G6O | 57.8 | 284 | 203.71 | 30.690 | 13,546 |
| G6N | 48.9 | 284 | 172.37 | 25.969 | 35,417 |
| G6J | 40.0 | 284 | 141.03 | 21.247 | 82,288 |
| G6M | 40.0 | 284 | 141.03 | 21.247 | 101,047 |
| G6K | 31.1 | 284 | 109.69 | 16.525 | 280,649 |
| G6L | 31.1 | 284 | 109.69 | 16.525 | 478,093 |

* test stopped before failure after more than 500,000 cycles

## TABLE 7 Results of Fatigue Loading of Carbon Fiber Rebars @ 1Hz

| Specimen Number | Maximum Force Applied (kips) | Equivalent Steel Bar Area (sq.in.) | Maximum Stress Applied (ksi) | Percent of Average Ultimate Load | Number of Cycles Before Failure |
|---|---|---|---|---|---|
| C4-7 | 22 | 0.20 | 110.00 | 89.752 | 286 |
| C4-8 | 22 | 0.20 | 110.00 | 89.752 | 616 |
| C4-9 | 19 | 0.20 | 95.00 | 77.513 | 36,456 |
| C4-10 | 19 | 0.20 | 95.00 | 77.513 | 8,745 |
| C4-11 | 17 | 0.20 | 85.00 | 69.354 | 171,178 |
| C4-12 | 17 | 0.20 | 85.00 | 69.354 | 520,222* |
| C4-13 | 15 | 0.20 | 75.00 | 61.195 | 515,116* |
| C4-15 | 12 | 0.20 | 60.00 | 48.956 | 520,438* |
| C5-7b | 32 | 0.31 | 103.23 | 91.467 | 1,115 |
| C5-8 | 32 | 0.31 | 103.23 | 91.467 | 820 |
| C5-9 | 29 | 0.31 | 93.55 | 82.892 | 1,919 |
| C5-13 | 29 | 0.31 | 93.55 | 82.892 | 5 |
| C5-10 | 25 | 0.31 | 80.65 | 71.459 | 87,596 |
| C5-11 | 25 | 0.31 | 80.65 | 71.459 | 884 |
| C5-14 | 25 | 0.31 | 80.65 | 71.459 | 752 |
| C5-12 | 21 | 0.31 | 67.74 | 60.025 | 87,759 |
| C5-15 | 21 | 0.31 | 67.74 | 60.025 | 2,396 |
| C5-7a | 18 | 0.31 | 58.06 | 51.451 | 514,176* |
| C6-7 | 43 | 0.44 | 97.73 | 91.194 | 120 |
| C6-8 | 43 | 0.44 | 97.73 | 91.194 | 1,062 |
| C6-9 | 38 | 0.44 | 86.36 | 80.590 | 76,491 |
| C6-10 | 38 | 0.44 | 86.36 | 80.590 | 129,600 |
| C6-11 | 33 | 0.44 | 75.00 | 69.986 | 333,031 |
| C6-12 | 33 | 0.44 | 75.00 | 69.986 | 197,074 |
| C6-13 | 28 | 0.44 | 63.64 | 59.382 | 479,774 |
| C6-14 | 28 | 0.44 | 63.64 | 59.382 | 460,784 |
| C6-15 | 24 | 0.44 | 54.55 | 50.899 | 518,382* |

* test stopped before failure after more than 500,000 cycles

## TABLE 7m Results of Fatigue Loading of Carbon Fiber Rebars @ 1Hz

| Specimen Number | Maximum Force Applied (kN) | Equivalent Steel Bar Area (sq.mm) | Maximum Stress Applied (MPa) | Percent of Average Ultimate Load | Number of Cycles Before Failure |
|---|---|---|---|---|---|
| C4-7 | 97.9 | 129 | 758.42 | 89.752 | 286 |
| C4-8 | 97.9 | 129 | 758.42 | 89.752 | 616 |
| C4-9 | 84.5 | 129 | 655.00 | 77.513 | 36,456 |
| C4-10 | 84.5 | 129 | 655.00 | 77.513 | 8,745 |
| C4-11 | 75.6 | 129 | 586.05 | 69.354 | 171,178 |
| C4-12 | 75.6 | 129 | 586.05 | 69.354 | 520,222* |
| C4-13 | 66.7 | 129 | 517.11 | 61.195 | 515,116* |
| C4-15 | 53.4 | 129 | 413.69 | 48.956 | 520,438* |
| C5-7b | 142.3 | 199 | 711.79 | 91.467 | 1,115 |
| C5-8 | 142.3 | 199 | 711.79 | 91.467 | 820 |
| C5-9 | 129.0 | 199 | 645.00 | 82.892 | 1,919 |
| C5-13 | 129.0 | 199 | 645.00 | 82.892 | 5 |
| C5-10 | 111.2 | 199 | 556.06 | 71.459 | 87,596 |
| C5-11 | 111.2 | 199 | 559.06 | 71.459 | 884 |
| C5-14 | 111.2 | 199 | 559.06 | 71.459 | 752 |
| C5-12 | 93.4 | 199 | 467.05 | 60.025 | 87,759 |
| C5-15 | 93.4 | 199 | 467.05 | 60.025 | 2,396 |
| C5-7a | 80.1 | 199 | 400.31 | 51.451 | 514,176* |
| C6-7 | 191.3 | 284 | 673.82 | 91.194 | 120 |
| C6-8 | 191.3 | 284 | 673.82 | 91.194 | 1,062 |
| C6-9 | 169.0 | 284 | 595.43 | 80.590 | 76,491 |
| C6-10 | 169.0 | 284 | 595.43 | 80.590 | 129,600 |
| C6-11 | 146.8 | 284 | 517.11 | 69.986 | 333,031 |
| C6-12 | 146.8 | 284 | 517.11 | 69.986 | 197,074 |
| C6-13 | 124.6 | 284 | 438.78 | 59.382 | 479,774 |
| C6-14 | 124.6 | 284 | 438.78 | 59.382 | 460,784 |
| C6-15 | 106.8 | 284 | 376.11 | 50.899 | 518,382* |

* test stopped before failure after more than 500,000 cycles

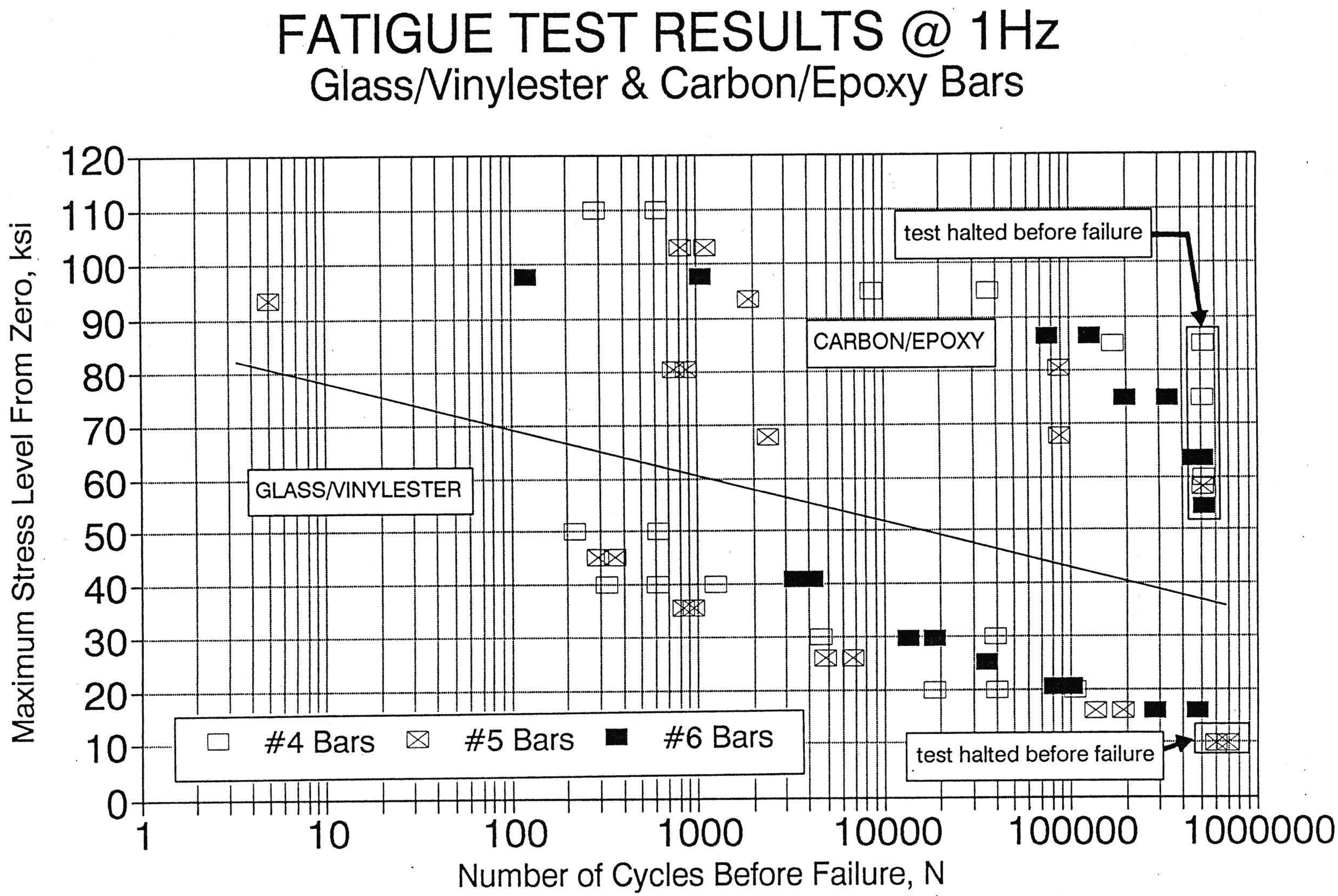


**Figure 3 Stress Level Versus Number of Cycles To Failure**

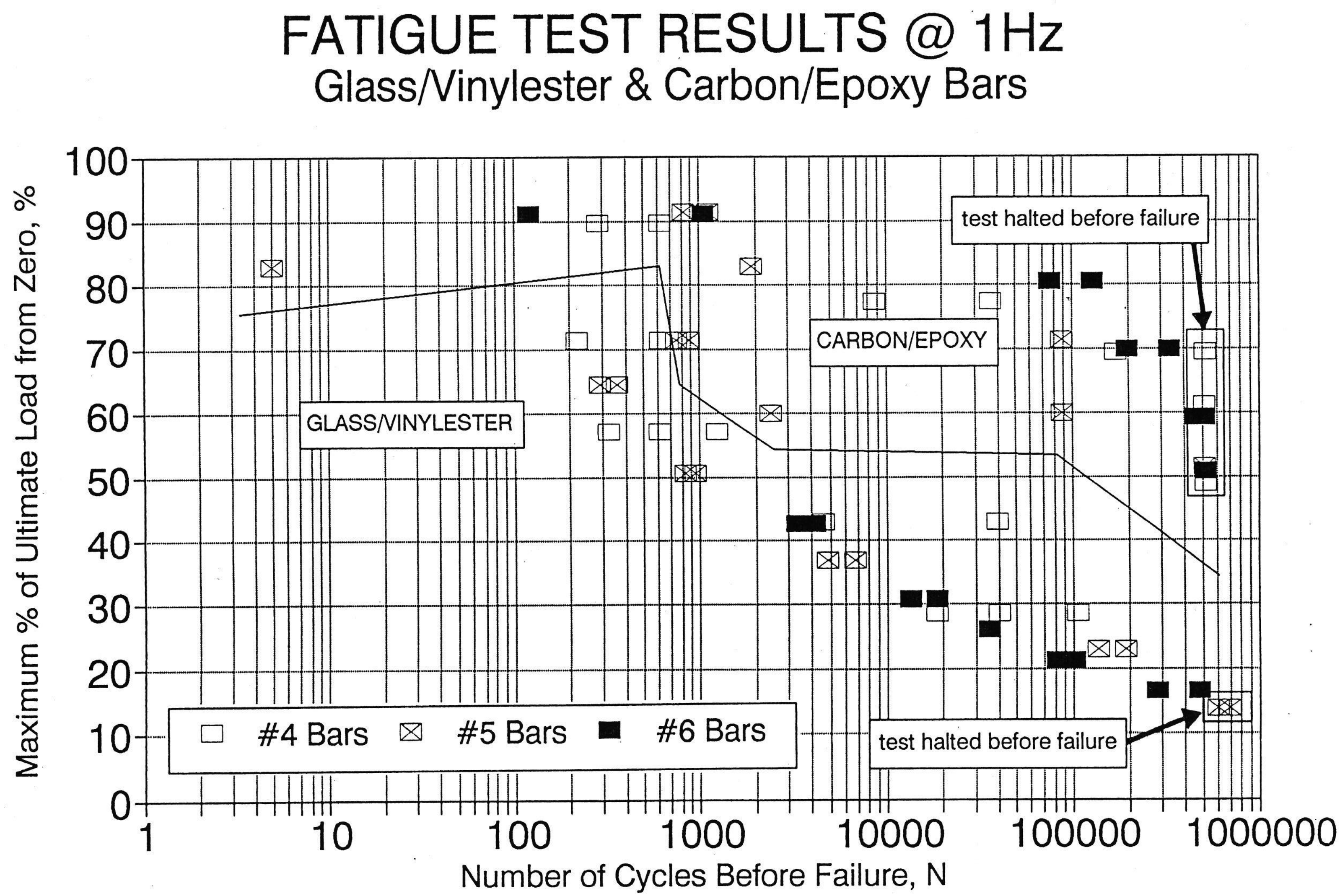


Figure 4 Percent of Ultimate Load Vs. Number of Cycles to Failure

### 3.2 Testing for Bond Strength

Tables 8A and 8B list the results of the bond tests giving specimen number, bar material, bar size, embedment length, concrete strength, force at failure, average bond stress, and the resulting **k** variable. For each size bar, the average, standard deviation, and coefficient of variation for the **k** value are given. Also given is the value of the **k** variable divided by 35. The value of 35 for a **k** variable presently underlies the calculation of basic development lengths in the ACI Code for steel reinforcement. The value of that ratio indicates how much longer the development length of the GFRP bar would be than that for a steel bar of the same size.

The **k** variable is defined by the relationship, $l_d = A_b f_b / k\sqrt{f'_c}$ . . .

where $l_d$ is the length of embedment in inches necessary to develop the force, $A_b f_b$,

$A_b$ is the cross-sectional area of the bar in inches,

$f_b$ is the stress in the bar in psi,

$f'_c$ is the twenty-eight day strength of the concrete in psi, and

$k$ is the normalizing constant to be evaluated.

From the test results, **k** is evaluated by dividing the force at slip failure by the product of the length of embedment and the square root of the 28-day concrete strength, $f'_c$. That is, $k = F / l_d\sqrt{f'_c}$. The ratios of the average values of **k**, each for a given bar size, divided by 35 indicate increasingly better development length values for increasing bar size. These results are consistent with earlier bond strength tests done at the University of Arkansas of GFRP bars from a different Arkansas manufacturer [Pleimann, 1991].

The average results suggest that one would need a 75%, 31%, and 7% increase in the development lengths of the #'s 4, 5, and 6 (13, 16, and 19 metric) GFRP rebars respectively.

## TABLE 8A Bond Strength Results in 3050 psi Concrete of GFRP Rebars

| Specimen Number | Bar Type | Bar Size | Embedment Length (ins) | Average Ultimate Concrete Strength (psi) | Force at Slip Failure (lbs) | Average Bond Stress (psi) | Calculated k Factor |
|---|---|---|---|---|---|---|---|
| FD4E6T1 | FRP | 4 | 6 | 3050 | 7100 | 753.3 | 21.43 |
| FD4E6T4 | FRP | 4 | 6 | 3050 | 8400 | 891.3 | 25.35 |
| FD4E6T5 | FRP | 4 | 6 | 3050 | 4500 | 477.4 | 13.58* |
| FD4E8T6 | FRP | 4 | 8 | 3050 | 9400 | 748.0 | 21.28 |
| FD4E8T7 | FRP | 4 | 8 | 3050 | 8700 | 692.3 | 19.69 |
| FD4E8T2 | FRP | 4 | 8 | 3050 | 7800 | 620.7 | 17.65 |
| FD4E10T9 | FRP | 4 | 10 | 3050 | 9100 | 579.3 | 16.48 |
| FD4E10T10 | FRP | 4 | 10 | 3050 | N/A | N/A | N/A |
| FD4E10T11 | FRP | 4 | 10 | 3050 | 9550 | 636.6 | 17.29 |
| SD4E8T8 | STEEL | 4 | 8 | 3050 | 10100 | 803.7 | 22.86 |
| SD4E8T12 | STEEL | 4 | 8 | 3050 | 14200 | 1130.0 | 32.14 |
| SD4E8T3 | STEEL | 4 | 8 | 3050 | 13900 | 1106.1 | 31.46 |
| STATISTICAL VALUES FOR #4 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 19.88<br>3.10<br>0.156<br>1.751 |
| FD5E75T13 | FRP | 5 | 7.5 | 3050 | 11000 | 747.0 | 26.56 |
| FD5E75T14 | FRP | 5 | 7.5 | 3050 | 12300 | 835.2 | 29.70 |
| FD5E75T15 | FRP | 5 | 7.5 | 3050 | 8900 | 604.4 | 21.49 |
| FD5E10T16 | FRP | 5 | 10 | 3050 | 16700 | 850.5 | 30.24 |
| FD5E10T17 | FRP | 5 | 10 | 3050 | 17900 | 911.6 | 32.41 |
| FD5E10T18 | FRP | 5 | 10 | 3050 | 11300 | 575.5 | 20.46 |
| SD5E10T19 | STEEL | 5 | 10 | 3050 | 22100 | 1125.5 | 40.02 |
| SD5E10T20 | STEEL | 5 | 10 | 3050 | 24300 | 1237.6 | 44.00 |
| SD5E10T21 | STEEL | 5 | 10 | 3050 | 16250 | 827.6 | 29.42 |

* not used in calculating average

TABLE 8Am Bond Strength Results in 21.029 MPa Concrete of GFRP Rebars

| Specimen Number | Bar Type | Metric Bar Size | Embedment Length (cm) | Average Ultimate Concrete Strength (MPa) | Force at Slip Failure (kN) | Average Bond Stress (MPa) | Calculated **k** Factor |
|---|---|---|---|---|---|---|---|
| FD4E6T1 | FRP | 13 | 15.24 | 21.029 | 31.582 | 5.193 | 21.43 |
| FD4E6T4 | FRP | 13 | 15.24 | 21.029 | 37.365 | 6.145 | 25.35 |
| FD4E6T5 | FRP | 13 | 15.24 | 21.029 | 20.017 | 3.292 | 13.58* |
| FD4E8T6 | FRP | 13 | 20.32 | 21.029 | 41.813 | 5.157 | 21.28 |
| FD4E8T7 | FRP | 13 | 20.32 | 21.029 | 38.700 | 4.773 | 19.69 |
| FD4E8T2 | FRP | 13 | 20.32 | 21.029 | 34.696 | 4.280 | 17.65 |
| FD4E10T9 | FRP | 13 | 25.40 | 21.029 | 40.479 | 3.994 | 16.48 |
| FD4E10T10 | FRP | 13 | 25.40 | 21.029 | N/A | N/A | N/A |
| FD4E10T11 | FRP | 13 | 25.40 | 21.029 | 42.481 | 4.389 | 17.29 |
| SD4E8T8 | STEEL | 13 | 20.32 | 21.029 | 44.927 | 5.541 | 22.86 |
| SD4E8T12 | STEEL | 13 | 20.32 | 21.029 | 63.165 | 7.791 | 32.14 |
| SD4E8T3 | STEEL | 13 | 20.32 | 21.029 | 61.830 | 7.626 | 31.46 |
| STATISTICAL VALUES FOR #13 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 19.88<br>3.10<br>0.156<br>1.751 |
| FD5E75T13 | FRP | 16 | 19.05 | 21.029 | 48.930 | 5.150 | 26.56 |
| FD5E75T14 | FRP | 16 | 19.05 | 21.029 | 54.713 | 5.759 | 29.70 |
| FD5E75T15 | FRP | 16 | 19.05 | 21.029 | 39.589 | 4.167 | 21.49 |
| FD5E10T16 | FRP | 16 | 25.40 | 21.029 | 74.285 | 5.864 | 30.24 |
| FD5E10T17 | FRP | 16 | 25.40 | 21.029 | 79.623 | 6.285 | 32.41 |
| FD5E10T18 | FRP | 16 | 25.40 | 21.029 | 50.265 | 3.968 | 20.46 |
| SD5E10T19 | STEEL | 16 | 25.40 | 21.029 | 98.306 | 7.760 | 40.02 |
| SD5E10T20 | STEEL | 16 | 25.40 | 21.029 | 108.092 | 8.533 | 44.00 |
| SD5E10T21 | STEEL | 16 | 25.40 | 21.029 | 72.284 | 5.706 | 29.42 |

* not used in calculating average

## TABLE 8B Bond Strength Results in 2500 psi Concrete of GFRP Rebars

| Specimen Number | Bar Type | Bar Size | Embedment Length (ins) | Average Ultimate Concrete Strength (psi) | Force at Slip Failure (lbs) | Average Bond Stress (psi) | Calculated k Factor |
|---|---|---|---|---|---|---|---|
| FD5E10T34 | FRP | 5 | 10 | 2500 | 13250 | 674.8 | 26.50 |
| FD5E10T35 | FRP | 5 | 10 | 2500 | 11700 | 595.9 | 23.40 |
| FD5E10T36 | FRP | 5 | 10 | 2500 | 13500 | 687.5 | 27.00 |
| FD5E12T31 | FRP | 5 | 12 | 2500 | 16300 | 691.8 | 27.17 |
| FD5E12T32 | FRP | 5 | 12 | 2500 | 19400 | 823.4 | 32.33 |
| FD5E12T33 | FRP | 5 | 12 | 2500 | 14500 | 615.4 | 24.17 |
| SD5E10T37 | STEEL | 5 | 10 | 2500 | N/A | N/A | N/A |
| SD5E10T38 | STEEL | 5 | 10 | 2500 | 20200 | 1028.8 | 40.40 |
| SD5E10T39 | STEEL | 5 | 10 | 2500 | 20000 | 1018.6 | 40.00 |
| STATISTICAL VALUES FOR #5 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 26.79<br>3.93<br>0.147<br>1.307 |
| FD6E9T22 | FRP | 6 | 9 | 2500 | N/A | N/A | N/A |
| FD6E9T23 | FRP | 6 | 9 | 2500 | N/A | N/A | N/A |
| FD6E9T24 | FRP | 6 | 9 | 2500 | 13900 | 655.5 | 30.89 |
| FD6E12T28 | FRP | 6 | 12 | 2500 | 19000 | 672.0 | 31.67 |
| FD6E12T29 | FRP | 6 | 12 | 2500 | 23700 | 838.2 | 39.50 |
| FD6E12T30 | FRP | 6 | 12 | 2500 | N/A | N/A | N/A |
| FD6E13T25 | FRP | 6 | 13 | 2500 | 18100 | 590.9 | 27.85 |
| FD6E12T26 | FRP | 6 | 13 | 2500 | N/A | N/A | N/A |
| FD6E13T27 | FRP | 6 | 13 | 2500 | 22000 | 718.2 | 33.85 |
| SD6E12T40 | STEEL | 6 | 12 | 2500 | N/A | N/A | N/A |
| SD6E12T41 | STEEL | 6 | 12 | 2500 | N/A | N/A | N/A |
| SD6E12T42 | STEEL | 6 | 12 | 2500 | N/A | N/A | N/A |
| STATISTICAL VALUES FOR #6 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 32.75<br>4.34<br>0.133<br>1.069 |

## TABLE 8Bm Bond Strength Results in 17.237 MPa Concrete of GFRP Rebars

| Specimen Number | Bar Type | Metric Bar Size | Embedment Length (cm) | Average Ultimate Concrete Strength (MPa) | Force at Slip Failure (kN) | Average Bond Stress (MPa) | Calculated **k** Factor |
|---|---|---|---|---|---|---|---|
| FD5E10T34 | FRP | 16 | 25.4 | 17.237 | 58.939 | 4.653 | 26.50 |
| FD5E10T35 | FRP | 16 | 25.4 | 17.237 | 52.044 | 4.109 | 23.40 |
| FD5E10T36 | FRP | 16 | 25.4 | 17.237 | 60.051 | 4.740 | 27.00 |
| FD5E12T31 | FRP | 16 | 30.5 | 17.237 | 72.506 | 4.770 | 27.17 |
| FD5E12T32 | FRP | 16 | 30.5 | 17.237 | 86.295 | 5.677 | 32.33 |
| FD5E12T33 | FRP | 16 | 30.5 | 17.237 | 64.499 | 4.243 | 24.17 |
| SD5E10T37 | STEEL | 16 | 25.4 | 17.237 | N/A | N/A | N/A |
| SD5E10T38 | STEEL | 16 | 25.4 | 17.237 | 89.854 | 7.093 | 40.40 |
| SD5E10T39 | STEEL | 16 | 25.4 | 17.237 | 88.964 | 7.023 | 40.00 |
| STATISTICAL VALUES FOR #16 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 26.79<br>3.93<br>0.147<br>1.307 |
| FD6E9T22 | FRP | 19 | 22.9 | 17.237 | N/A | N/A | N/A |
| FD6E9T23 | FRP | 19 | 22.9 | 17.237 | N/A | N/A | N/A |
| FD6E9T24 | FRP | 19 | 22.9 | 17.237 | 61.830 | 4.920 | 30.89 |
| FD6E12T28 | FRP | 19 | 30.5 | 17.237 | 84.516 | 4.633 | 31.67 |
| FD6E12T29 | FRP | 19 | 30.5 | 17.237 | 105.423 | 5.779 | 39.50 |
| FD6E12T30 | FRP | 19 | 30.5 | 17.237 | N/A | N/A | N/A |
| FD6E13T25 | FRP | 19 | 33.0 | 17.237 | 80.513 | 4.074 | 27.85 |
| FD6E12T26 | FRP | 19 | 33.0 | 17.237 | N/A | N/A | N/A |
| FD6E13T27 | FRP | 19 | 33.0 | 17.237 | 97.861 | 4.952 | 33.85 |
| SD6E12T40 | STEEL | 19 | 30.5 | 17.237 | N/A | N/A | N/A |
| SD6E12T41 | STEEL | 19 | 30.5 | 17.237 | N/A | N/A | N/A |
| SD6E12T42 | STEEL | 19 | 30.5 | 17.237 | N/A | N/A | N/A |
| STATISTICAL VALUES FOR #19 FRP BARS<br>Calculated **k** Factor | | | | | Average, **X**<br>Standard Deviation<br>Coefficient/Variation<br>35/**X** | | 32.75<br>4.34<br>0.133<br>1.069 |

# 4. CONCLUSIONS AND RECOMMENDATIONS

Despite the limited number of tests performed, and the scatter of data in the CFRP results because of the inconsistency of the hand production procedure, valuable information can be extrapolated from the results. Following is an interpretation of the test data, recommendations for the application of GFRP rebars and CFRP rebars in transportion structures, and recommendations regarding further research that should be done in this area of interest.

## 4.1 Interpretation of Test Results

### 4.1.1 Tension Strength and Modulus of Elasticity Tests

The data received from the reported tests may be summarized in the following manner. The GFRP bars were consistent in their strength, averaging 70 ksi (482.6 MPa) ultimate stress for the #4 (#13m) and #5 (#16m) bars, and 95 ksi (655.0 MPa) for the #6 (#19m) bars. The #4 (#13m), #5 (#16m), and #6 (#19m) bars showed average moduli of elasticity of 4.9 (33.8), 5.3 (36.5), and 6.0 (41.4) million psi (GPa) respectively.

The major difference in the strength results for GFRP bars between the two smaller bar sizes and the larger one indicates the effect of two factors that should be discussed at this point. First is the relationship between the "steel" rebar sizes and the FRP rebar sizes. Manufacturers of the FRP bars adopt similar size designations so that the users of their product will be comfortable with numbers they already know from design with steel rebar sizes. However, often the FRP bars are manufactured by die sizes and wrapping processes that instead produce differences between the "steel" and FRP rebar cross-sectional areas for the same "size."

Examination of Figure 2 shows a tight concentration of results for the same GFRP bar size, especially the two larger sizes. Theoretically, the stress capacity of a unit area of uniaxial fibers with the same percentage of fiber and matrix should be the same. But the cross-sectional areas that are divided into the ultimate force may not be truly representative of the actual effective cross-sectional area.

The other factor that affects the tensile stress capacity results is the longitudinal configuration of the fibers. In the attempt to put a deformation in the outer surface of the bars for bond strength, normally an additional fiber roving strand or two are wrapped around the bar before it hardens. This creates a helical depression around the rebar surface and places the outer fibers in a non-uniaxial configuration. It is these outer fibers that are initially stressed as the surface bond initiates the tendency toward a uniform tension stress across the rebar cross section. These outer non-uniaxial fibers cannot resist with the same capacity as the inner uniaxially oriented fibers. The outer deformation, composed of non-uniaxial fibers, may well affect a constant absolute length of the outer portion of the radius of the bar cross section. That means that the proportion of the inner core of uniaxial fibers may be a larger percentage of the total bar cross-sectional "area" in the larger sized bars than in the smaller ones. This would make the larger sized bars indicate a stronger stress capacity than the smaller sized bars, which is consistent with our results.

An Iowa State University researcher [Porter, 1994] told the author that he had developed a relationship between the cosine of the steepest angle of the fibers relative to the longitudinal axis and the stress capacity reduction of the bar. The author was told [Gauchel, 1994] that the ASTM committee currently discussing the proper cross section to use in the evaluation of the stress capacity was suggesting the use of the net uniaxial core area within the deformations. This would seem to put a premium on optimizing the uniaxial cross sectional area. Thus an "ideal" FRP rebar would be one that would emerge with a smooth surface from the pultrusion die and then have a deformed surface added to it afterward. The development of such a bar would require expertise in polymer science and the possibility of adhesion between the previously pultruded smooth surface and the added deformation. This is a very important area of future research.

In any case, these factors make for an inescapably difficult evaluation of the tensile strength of FRP rebars that are "deformed" by means of a helical wrap before the main portion of the bar is fully polymerized. In the meantime, it might well be better for designers to work with the average **force** capacity of a given FRP bar "size" rather than a **stress** capacity. A minimum ultimate force capacity of the bars would need to be guaranteed by the manufacturer rather than a stress capacity.

The results for the CFRP bars were more scattered because of the hand manufacture. The carbon bars showed an average ultimate tensile strength of 122.5 (844.6), 125.7 (866.7), and 107.2 (739.1) ksi (GPa) for the #4 (#13m), #5 (#16m), and #6 (#19m) bars respectively. The #4 (#13m), #5 (#16m), and #6 (#19m) bars showed average modulii of elasticity of 11.3 (77.9), 12.2 (84.1), and 10.9 (75.2) million psi (GPa) respectively. The carbon fiber bars are obviously superior to the glass fiber bars in both strength and stiffness. With carefully controlled pultrusion production this superiority could well be increased.

### 4.1.2 Bond Pull-Out Tests

The bond pull-out tests indicated that the coefficient, **k**, varied with size of bar, having an average value of 19.88, 26.79, and 32.75 for #4 (#13m), #5 (#16m), and #6 (#19) glass reinforced (GFRP) rebars respectively. This indicates the need for development lengths some 75%, 31%, and 7% greater than the current ACI Code formulation for individual steel rebars of the same respective "size." This tendency for increased bond capacity with increasing bar size is consistent with earlier tests done at the University of Arkansas on GFRP bars from a different manufacturer [Pleimann, 1991]. There is no reason why carbon fiber reinforced (CFRP) bars in a compatible vinylester matrix should not give similar bond strength results since the bond strength is primarily a function of the hardness of the matrix material for FRP rebars.

### 4.1.3 Fatigue Strength Tests

The results of the fatigue tests for both the GFRP and CFRP bars were summarized in Figures 3 and 4. The typical behavior of a brittle material as plotted on such an S-N diagram was apparent for both materials, except that again the results of the carbon fiber bars was much more scattered. By plotting tensile stress applied, or percent of ultimate load capacity versus number of cycles of loading to failure on a log scale, one obtained an essentially linear improvement of number of cycles of load possible as the applied stress level was reduced. Unfortunately the results are not conclusive as to the endurance limit of FRP rebars made of either material. The tests were stopped before the bar failed in fatigue if the number of cycles had exceeded 500,000. The symbols for such tests are included in Figures 3 and 4 but enclosed in a rectangle with a note "test halted before failure." A few of the symbols enclosed in the rectangle represent failure very near, but less than 500,000 cycles. The difference can be identified by comparing the Figures 3 and 4 with the data in Tables 6 and 7 where the number of cycles for the halted tests has an asterisk added.

If the tests could have been continued beyond 500,000 cycles the endurance limit of the material might have been established. This would have been particularly helpful because the endurance limit could then be used as an allowable stress in a Working Stress Design approach to the use of the rebars under any number of repeated loads. One of the few papers available that examines the fatigue characteristics of GFRP bars [Chaallal and Benmokrane, 1993] is reporting on a bar with the bond resistance gained by the use of a double-helix outer wrap on the bars. Each wrap is applied in an opposite rotational direction. Figure 5 from their paper is reproduced on the next page. It contains a limited amount of GFRP data plotted on a graph of steel fatigue data. Of perhaps even more significance is that the average "endurance limit" of steel ($S_r$) is only 166 MPa (24.1 ksi). This is in the order of the allowable stress for a Grade 60 steel rebar if one is using Working Stress Design. The ACI Code [ACI, 1995] still uses 20 ksi (137.9 MPa) as the allowable stress for Grade 40 and Grade 50 rebars, but only 24 ksi (165.5 MPa) for Grade 60 rebars. Interestingly, the 1983 edition of the ACI Committee 350 Report, "Concrete Sanitary Engineering Structures," permitted an allowable stress of 30 ksi (206.8 MPa) for Grade 60 rebars. Obviously reinforced concrete water treatment and waste water treatment tanks are not subject to rapidly repeated load so the fatigue strength restriction was relaxed and the factor-of-safety was consistent was that for Grade 40 bars. In the most recent edition of the report, ACI 350R-89, the allowable has been reduced to 27 ksi (186.2 MPa) but because of crack control considerations.

A consideration of Figures 3 and 4 indicates that the endurance limit for the GFRP bars is less than or equal to 15 ksi (103.4 MPa), that of CFRP rebars is less than or equal to possibly as much as 60 ksi (413.7 MPa). Obviously much work must be done to establish the endurance limit of these bars, to identify all the factors that influence the endurance limit and to move in the direction of an optimum fiber configuration for such bars and the means to manufacture them. In the meantime, the stresses mentioned above could well function as allowable stresses for the respective materials in statically loaded structures until the final endurance limit is established.

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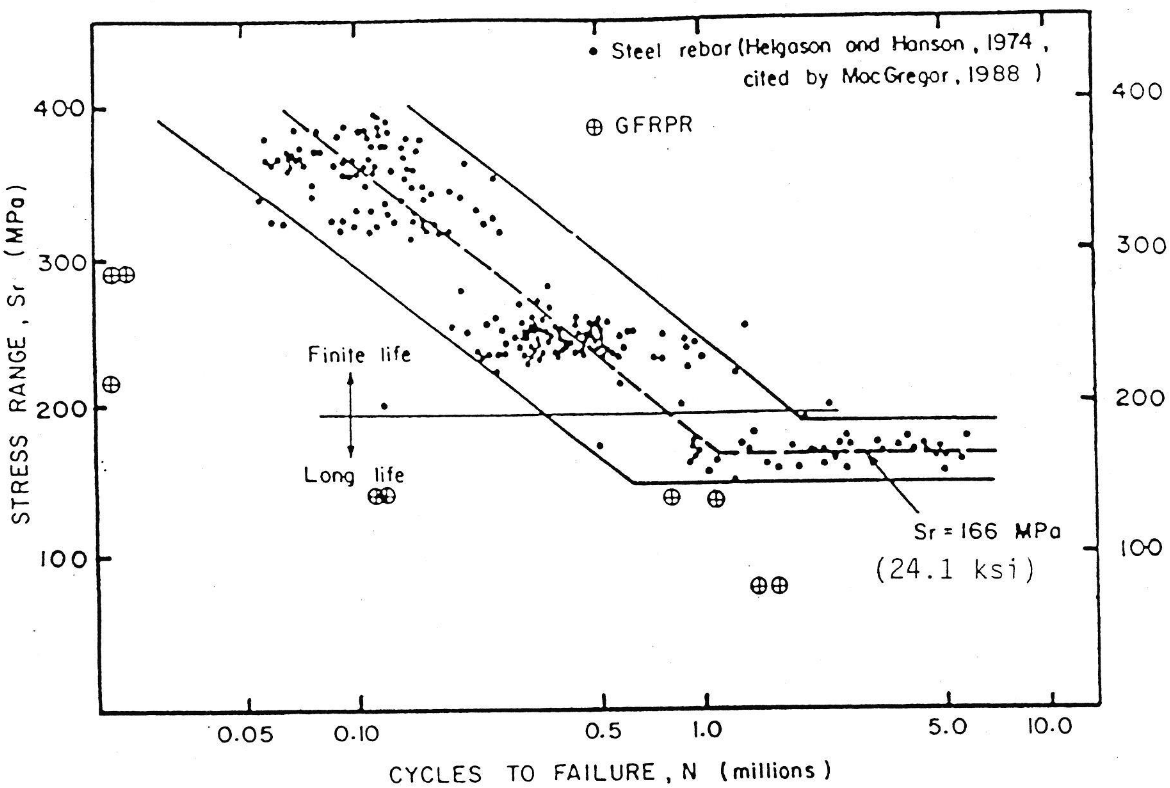


**Figure 5 Other GFRP Fatigue Data Compared With Steel (from Chaalial and Benmokrane)**

### 4.1.4 General Conclusions

Glass fiber reinforced polymer rods will continue to be the FRP bar of choice as reinforcement for Portland cement concrete structures for some time. The primary reasons are cost and strength. Glass fiber is available for about $0.70 to $0.80 per pound. The ultimate stresses available are competitive with steel. The disadvantage of GFRP rods is primarily their low stiffness. Their modulus-of-elasticity is only about one-sixth to one-fifth that of steel. This low modulus-of-elasticity results in excessive deflection and cracking in reinforced concrete structures unless it is countered by using a low allowable stress and/or short fibers mixed in the concrete to increase its tension strength.

Carbon fiber gives promise of a stiffer bar. The modulus-of-elasticity of carbon fiber is in the order of 31 million psi, above that of steel. Even embedded in a resin its stiffness properties should be superior to that of GFRP. Even the handmade CFRP rebars of this study had a stiffness in the order of twice that of the pultruded GFRP bars. CFRP bars also possess excellent strength and fatigue resistance in comparison with the glass fiber bars. The current drawback to using carbon fiber is its high cost. That price, in recent years, has reduced from more than $9/pound to about $5/pound today. Moreover, research has been reported in the last several years at the Chemical Engineering Department of West Virginia University which could lower the price of carbon fiber significantly. Researchers in Morgantown were developing the use of a special solvent combination for taking carbon directly from coal. Other researchers at Auburn University are investigating other procedures for lowering the production costs of carbon fiber.

Given the future of carbon FRP it is important that it has been included in this project and that its study be continued. A recent unpublished masters report at the University of Arkansas [White, 1997] did a rough comparison of costs of a 50 ft. (15.24 m) long two-lane bridge deck reinforced with conventional Grade 60 rebars as well as GFRP and CFRP rebars. The superior stiffness and strength of the CFRP bars in comparison to the GFRP ones made the former competitive with the latter despite the higher costs. Also, if one assumed one replacement of the steel reinforced deck and no replacement of the FRP reinforced decks, the life-cycle cost of the FRP reinforced decks is already less than that of the conventional steel reinforced deck.

Another factor possibly influencing the use of FRP bars for reinforcement would be their behavior in actual beams. The bars tested in this program were in direct tension. One could observe a kind of "rotation" of the cross section as it deflected and stretched under repeated load. That kind of behavior probably added to the fatigue effect on the outer fibers beginning a progressive failure. If the outer wrapping were double and the wraps oppositely directed they would provide a symmetry that could counter the rotational effect.

Also, the bars in this project were tested in "bare" tension. In a beam they would be "enclosed" by the surrounding concrete. The endurance limit for steel is not far above the allowable stress for Grade 60 rebars in Working Stress Design procedures, yet the fatigue behavior of steel reinforced concrete beams is seldom examined. The fatigue strength of the FRP bars in beams may give different results than in direct tension tests.

On the basis of the results obtained from the described tests of FRP bars the following summary conclusions are tenable:

1. FRP rods of each typical bar size exhibit strengths that are consistent and usable for Portland cement concrete reinforcement when manufactured by a proven production method such as pultrusion.

2. The load-deformation behavior of the bars is essentially linear from zero load to failure. Therefore, any flexural ductility desired will be limited to that provided by the non-linear character of the Portland cement concrete stress-strain curve. Therefore, Working Stress Design procedures are probably better suited to flexural design using FRP reinforcement.

3. The use of a proper allowable strength for the FRP bars for Working Stress flexural design will require a decision on the part of the design engineer. For statically loaded flexural sections the allowable should be less than or equal to half the ultimate stress or force capacity of the bar.

4. Subjecting a partially polymerized FRP bar to a helical wrap is the most typical method of producing surface deformations on pultruded bars. This procedure causes a reduction of strength in those fibers that are no longer uniaxial, i.e., not parallel to the longitudinal axis of the bar. A better FRP reinforcement bar would be one that would have surface

deformations added to a smooth surfaced pultruded bar in which all the fibers are uniaxial.

5. Bond strength characteristics of the bars produced with the outer helical wrap are adequate for safe design. The percentage increase in necessary development length as compared to steel bars of the same "size" will reduce as the bar size increases.

6. The modulii of elasticity of FRP rebars produced with external deformations from helical wrap are significantly lower than the MOE value for steel bars. The MOE can be assumed to be about 6 million psi (41.4 GPa) for GFRP rebars, and about 11 million psi (75.8 GPa) for CFRP rebars.

7. FRP bars exhibit strength reduction under repeated load. The value of their endurance limits is as yet unknown. Under 500,000 repeated loads at 1 Hz GFRP rebars could be assumed to have a fatigue strength of about 15 ksi (103.4 MPa), and the CFRP rebars could be assumed to have a fatigue strength of about 60 ksi (413.7 MPa). Working Stress Design procedures for flexural sections could use the fatigue strength of the bars as a design allowable stress it it were known for a given number of load repetitions. If the endurance limit were known then that could become the allowable design stress for any number of repetitive loads.

## 4.2 Recommendations for Applications

On the basis of the limited tests performed in this project for FRP rebars, the following recommendations can be made:

1. FRP bars can be safely used as reinforcement in concrete structures not subject to repeated load. Flexural sections should be designed by Working Stress Design procedures using no more than half the static strength of the FRP bar as the allowable

stress or force. Proper attention in design must also be paid to the stiffness of the bars and the resulting cracking and deflection. These structures would include median barriers, railings, retaining walls, etc.

2. Manufacturers of the bars should meet specified minimum tensile force capacity and average modulus-of-elasticity, subject to compliance testing requirements as set by the Arkansas Highway and Transportation Department.

3. The use of FRP rebars as reinforcement in Portland cement concrete members subject to fatigue loads is still problematic. It is recommended that design of flexural members in this context also be done by Working Stress Design procedures using an allowable stress for the FRP rebar that is representative of the fatigue strength of the bar appropriate to the anticipated number of repeated loads in the design life of the member. Further research will be needed to establish the endurance limit for bars of each fiber type.

## 4.3 Recommendations for Further Research

Research should be continued in the area of FRP rebars using a variety of fibers including at least E-glass, carbon and high-stiffness aramid fibers such as KEVLAR-149. Future projects should include investigation of the following topics:

1. Tension capacity with investigation of the effect of the following factors:

    a) Comparison of static strength capacities and stiffnesses among a selection of the major national suppliers, including all the suppliers within the state of Arkansas.

    b) Investigation of the effect of a variety of factors on the strength of FRP bars of significant fiber types. The factors to be examined should include at the minimum:

1) Depth of deformation in the outer surface. Correlation between strength and the angle made by the deformation with the longitudinal axis of the bar should be sought.

2) Pitch, or length between deformation.

3) Strength of the uniaxial core of fibers.

4) Development of a mathematical model for predicting the final strength of bars with helical wrap outer deformations.

c) Development of a method of producing a pultruded bar with uniaxial fibers onto which can be attached a deformation pattern that will provide adequate bond strength. This will involve persons competent in polymer science as well as structural researchers.

2. Investigation of fatigue strength reduction including examination of the following factors:

a) Frequency of loading. The use of 6 Hz and 24 Hz is recommended.

b) Ratio of lower tensile stress to maximum tensile stress, and tensile stress range.

c) Fiber configuration including depth of deformation, pitch of the wrap, use of opposing directions of rotation, use of deformation applied to a smooth bar.

Later research should included the following:

3. Flexural behavior in half-scale reinforced concrete beams to failure using the most promising configuration of each type of fiber.

4. Fatigue strength of half-scale reinforced concrete beams under two levels of load and a 6 Hz frequency of load, using the most promising configuration of each type of fiber.

## LIST OF REFERENCES


Black, K. N., Larson, R. M., Staunton, L. R., "Evaluation of Stainless Steel Pipes for Use as Dowel Bars," **Public Roads**, Vol. 52, No. 2, 1988

Clear, K. C., "Effectiveness of Epoxy-Coated Reinforcing Steel," **Concrete International**, American Concrete Institute, Volume 14, No. 5, May 1992, pp. 58f.

Chaallal, O. and Benmokrane, B., "Physical and mechanical performance of an innovative glass-fiber-reinforced plastic rod for concrete and grouted anchorages," **Canadian Journal of Civil Engineering**, Vol. 20, No. 2, April 1993, p.254f.

Crumpton, C. F., "Concrete - A Faithful Servant," **TR News**, May-June 1985, #118, pp.3-7. See especially the scanning electron pho-tomicrographs of rust crystals in Figures 5A and 5B.

Faza, S. S., and GangaRao, H. V. S., "Behavior of Fiber Reinforced Plastic Rebar Under Bending and Bond," Transportation Research Board 69th Annual Meeting, Paper No.890441, January, 1990

Gauchel, James, private conversation, October, 1994. Mr. Gauchel is a researcher with the Owens-Corning Science-Technology Center in Granville, OH, and is secretary to the ASTM committee establishing Standard D2018.

Pleimann, L. G., "Strength, MOE, and Bond of Deformed FRP Rods," Proceedings of the ASCE Specialty Conference, **Advanced Composites Materials in Civil Engineering Structures**, Las Vegas, NV, January 31 & February 1, 1991.

Porter, Max, private conversation, October, 1994. Dr. Porter has performed significant research in recent years in the area of FRP uses in reinforced concrete structures.

Roll, R. D., private conversations regarding numerous projects for magnetic resonance imaging device installations done by Reynolds-Schlatner-Cheter-Roll, Inc., Consulting Engineers of San Antonio, Texas, under the design direction of Richard D. Roll.

White, Kevin T., "Comparison of FRP Reinforced Concrete Bridge Deck Design to Steel Reinforced Concrete Bridge Deck Design," unpublished Master of Science Report, Civil Engineering Department, University of Arkansas, May, 1997.