

Tensile characterization of glass FRP bars

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Abstract

The characterization of fiber reinforced polymer (FRP) bars for concrete reinforcement is necessary for design purposes as required by structural engineers, and for quality control/optimization purposes as required by bar manufacturers. This paper reports on a test protocol and the results obtained from a replicated experiment intended to yield a statistically valid estimate of the distribution of tensile strength in FRP bars. Four selected types of glass FRP (GFRP) bars with the same diameter were tested. In total, 32 bars from the same manufacturer were investigated. Instead of a polymeric resin-based anchor, a steel pipe filled with expansive cementitious grout was used as the end restrainer. An experiment based on a randomized complete block design was carried out to obtain data for statistical analysis. The analysis was carried out using a commercially available data analysis software program. This research project indicates that the suggested test procedure provides reliable data for tensile characterization and confirms that a Gaussian distribution can represent the tensile strength of the GFRP bars as tested.

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1. Introduction

Composite materials emerge as a promising alternative to correct the deficiencies caused by steel reinforcement in concrete structures [3,4,9,10,13–15,19] (Teng 2001).

The advantageous properties of fiber reinforced polymer (FRP) such as high strength-to-weight ratio, and corrosion and fatigue resistance create an interest in engineers. As given in Table 1, the ranges of properties for three FRP systems based on three different fibers (glass, carbon and aramid) are compared to those of conventional reinforcing steel. In addition to use in new construction, the results of field and laboratory investigations show the effectiveness of FRP bars as reinforcement for strengthening and rehabilitation applications. As an example, a strengthening method, consisting of the use of near-surface-mounted FRP bars, has been proposed for concrete and masonry structures [6,18].

For wide acceptance and implementation in construction, a full characterization of the mechanical properties of FRP bars is needed. In particular, it is necessary to define the mean value and distribution of the tensile strength of FRP bars for reinforced concrete, which engineers can use for design purposes and composite manufacturers for quality control and optimization purposes [8]. Various factors affect the tensile strength of FRP bars. The most significant factors are fiber type and fiber-volume fraction that is defined as the ratio of the volume of fiber to the overall volume of the bar over the unit length. Bar manufacturing process, quality control and the rate of thermoset resin curing also affect tensile strength [1].

This paper establishes a test protocol for tensile characterization and reports test results obtained on four types of glass FRP (GFRP) bars. Eight specimens of each type were tested to yield a statistically valid mean and distribution of tensile strength. Totally, 32 bars from the same manufacturer were investigated. The bars were anchored with a steel pipe filled with expansive cementitious grout.

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Table 1
Comparison of mechanical properties of FRP materials and steel (ACI 440.1R-01)

	Steel	GFRP	CFRP	AFRP
Nominal yield stress, MPa (ksi)	276–517 (40–75)	NA	NA	NA
Tensile strength, MPa (ksi)	482–689 (70–100)	482–1585 (70–230)	600–3688 (87–535)	1724–2537 (250–368)
Elastic modulus, $\times 10^3$ MPa ($\times 10^3$ ksi)	200 (29)	35–51 (5.1–7.4)	103–579 (15–84)	41–125 (6.0–18.2)
Yield strain (%)	1.4–2.5	NA	NA	NA
Ultimate strain (%)	6–12	1.2–3.1	0.5–1.9	1.9–4.4

The specimens were prepared in eight groups of four, with each bar type represented in each of the eight groups. The groups act as the ‘blocks’ in a randomized complete block (RCB) design, thus adjusting for any systematic trend in environmental factors or testing conditions across time. The bars with each group were prepared in random order, and the testing was carried out in the same order. The data obtained through the tests was analyzed using a statistical data analysis software program.

2. Material properties

2.1. GFRP bars

The GFRP bars used in this research program were manufactured by pultrusion using E-glass fibers and a thermoplastic resin. Bars produced using thermoplastic resin exhibit basic strength and modulus properties similar to those of thermoset materials containing an equivalent amount of fibers of the same type. Tensile strength varies with the cross-sectional dimensions of the bar due to shear lag effect, and therefore tensile strength should be referenced based on the bar size. Modulus is not significantly affected by the cross-sectional size of the bar,

but rather by level of fiber contained. Bars produced with 55% by volume of E-glass have been measured with a tensile modulus ranging from 40 to 47 GPa (5.8–6.8 Msi).

Bars produced using thermoplastic resin are unique in their ability to be post-formed. The thermoplastic composition allows for the fabrication of bends in the product long after it has left the pultrusion line. In addition, thermoplastic-based products can be welded together by localized melting of the two elements to be joined. This could be done by methods such as traditional contact heating, or with ultrasonic or radio frequency techniques. The ability to thermally weld may enable the production of lightweight reinforcing grids and meshes that can reduce on-project reinforcement placement costs. One potential concern regarding existing thermoset-based products is their lower resistance to damage from impact [12]. Construction sites present an environment where physical impacts due to handling and placement are commonplace. The impact toughness and damage tolerance of thermoplastic-based materials is significantly higher than that of thermoset-based materials [7].

The only difference among the four GFRP bar types used in this research program is the coating. All bars were #4 GFRP (1/2 in. or 12.5 mm in diameter) and had the same constituent materials, shape, and fiber-volume fraction, and the different coating resulted in different colors (Fig. 1). All

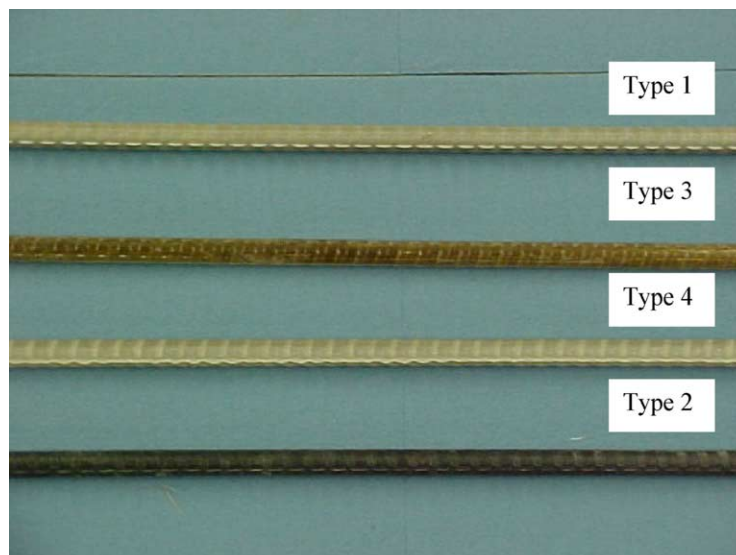


Fig. 1. Tested GFRP bars (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).



Fig. 2. Threaded end to improve anchorage.

four bar types consist of E-glass fibers in a matrix of rigid thermoplastic polyurethane. The only difference among all specimens, as mentioned, was in the coating, which is the key protective element against alkali attacks. Type 1 had short E-glass fibers in a matrix of Engineering Thermoplastic Polyurethane (ETPU); Type 2 had short carbon fibers in the ETPU; Type 3 had a matrix of pure ETPU; and Type 4 had Wollastonite (CaSiO_3) in the ETPU

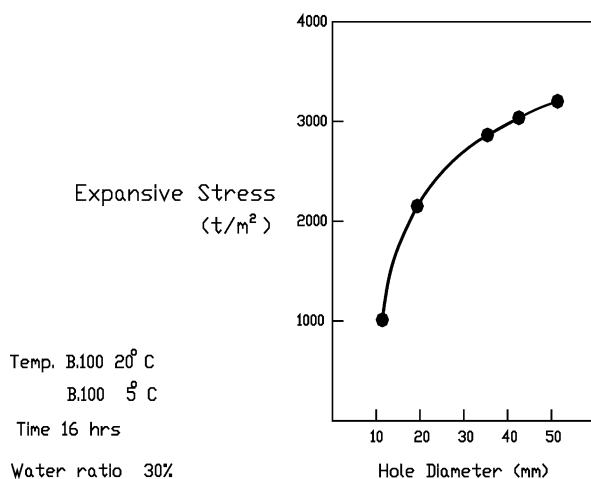


Fig. 3. Pressure as a function of pipe diameter.

(Wollastonite is used as a filler to replace sand and limestone in GFRP to reduce energy costs by lowering the fusion temperature).

Preliminary tensile tests indicated that direct pulling of the bar over a short length would cause the coating to separate from the core. This can be avoided by extending the anchorage length or creating a more suitable interlocking mechanism. An anchoring system was selected based on previous experience [11] and preliminary tests showed that this approach provided sufficient anchorage. The anchor consisted of using expansive cementitious grout, as explained in Section 2.2, and threading the FRP bars. The bars were threaded 8 in. (200 mm) from the end of the bar with five threads per in. (2 threads per cm) as shown in Fig. 2. The depth of the thread was selected as 0.12 in. (3 mm) to allow contact with the core material.

2.2. Specimen preparation

Anchorage and anchor alignment have a significant importance, as they may cause undesired failure modes. An anchorage system consisting of a steel pipe filled with an expansive cementitious grout was used to provide confinement pressure on the bar. Based on previous research [11] and preliminary tests, it was determined that 305 mm (12 in.) long anchors were sufficient for proper restraint. A total specimen length of $40d_b$ plus $2L_a$ is provided as recommended by unpublished ACI provisions [2], where d_b is the nominal diameter of the bar and L_a is the anchorage length. As per the data provided by the grout manufacturer, after 72 h, full expansion is developed and the water to powder ratio should be less than 0.34. For this experiment, a ratio of 0.29 is used. The maximum pressure developed is also a function of the pipe diameter (Fig. 3). Mechanical and physical properties of the pipes used are as follows: Nominal Pipe Size Designator: 1½ Schedule 80S, 1.9 in. (48.26 mm) outside diameter, 0.2 in. (5 mm) nominal wall thickness, and 30 ksi (205 MPa) yielding stress.

Plastic caps were used to close the ends of the pipes and to keep the bar in the center of the pipe. For this purpose, holes that are slightly larger than the bars were drilled at the center of the caps. Caps were inserted at one end of the pipes and the hole was closed with a piece of duck tape to prevent the grout from leaking. After this, the end of the bar was slid through the hole to on the duck tape. Wooden formwork was used to keep the bar and the pipe vertically aligned. The pipe was filled with expansive grout in this position. The other end of the pipe was also closed with another drilled cap through which the bar was inserted. The expansive grout was liquid when it was first prepared, and it needed 24 h to harden so that the specimen could be turned and the second anchor prepared. Before starting the tensile test, the plastic caps are removed.

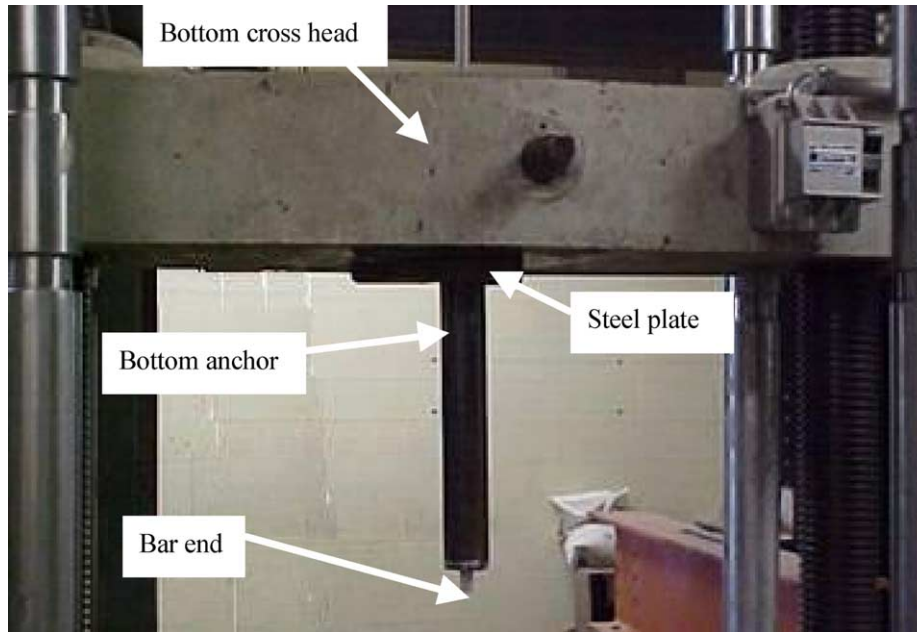


Fig. 4. Bottom anchor.

2.3. Sample groups

Four types of GFRP bars, as shown in Fig. 1, are evaluated. For each type, eight specimens were prepared and tested. The sample to be tested was divided into eight groups, which represents the blocks in a RCB design with

every block containing one specimen type of each. The tests of the four bars within each group were run consecutively, but in random order. Since all four bars in a group were tested within a short period of time (1 h) it is assumed that the test conditions within a group were similar. Also, for each group, a single batch of cementitious grout was

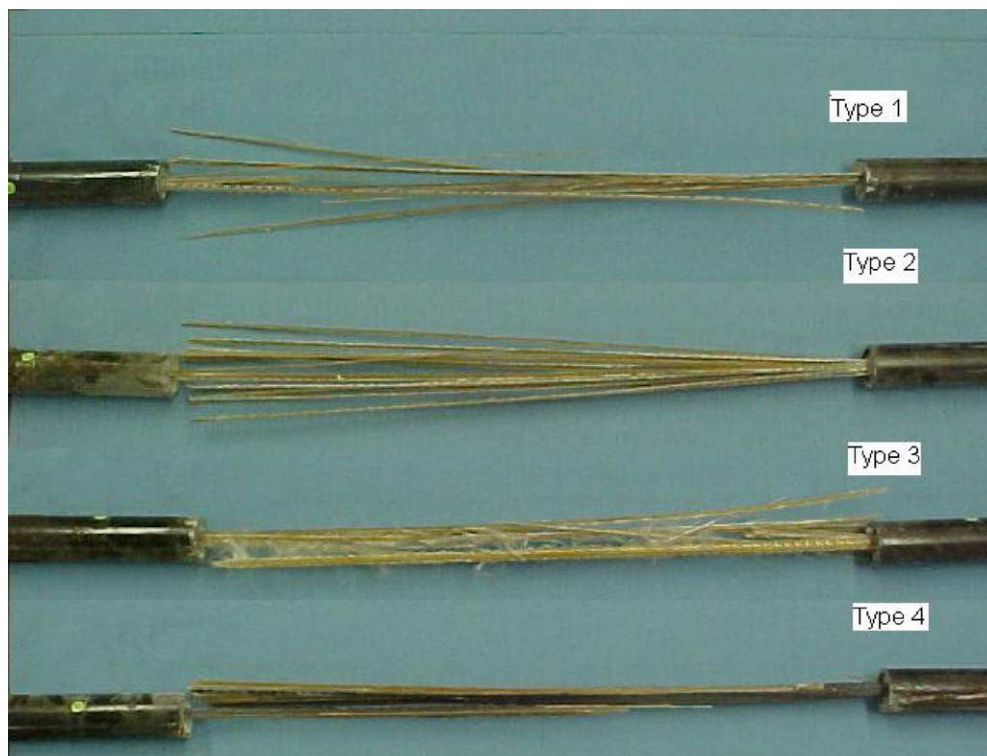


Fig. 5. Failure modes.



Fig. 6. Failure mode of Type 1.

Table 2
ANOVA (analysis of variance) table—load and strength

Source of variation	Degree of freedom	Sum of squares (load)	Mean square (load)	Sum of squares (strength)	Mean square (strength)	F-value	P-value
Block	7	85 112 250	1 215 893	220 766 702	31 538 100		
Type	3	50 243 125	16 747 708	1 303 217 379	434 405 793	0.56	0.7806
Error	21	45 715 625	2 176 934	1 185 782 077	56 465 813	7.69	0.0012
Corrected total	31	104 470 000	–	2 709 766 158	–	–	–

prepared, thus eliminating any variation due to grout differences among the bars within each group. This experimental procedure is consistent with the RCB design, with groups acting as blocks. This blocking reduces variations due to changes in test conditions over time.

2.4. Tensile test

The tests were conducted in the same order as the specimens were prepared so that the time between preparation and testing was the same for all bars. A universal testing machine was used for the tests. The top end of the specimen was fixed by the grips on the top cross-head of the machine while the bottom end was not fixed before applying the load. A slotted steel plate was placed between the top of the bottom anchor and the bottom of the middle cross-head. When the specimen was loaded, this plate engaged the bottom anchor (Fig. 4). The load was applied at a constant speed until the failure of the specimen.

2.5. Test results and data analysis

All specimens failed suddenly as expected. Fig. 5 shows the failure mode of representative specimens for each bar type. All the failures start with splitting (Fig. 6) and end with rupture of the bar. Every bar splits into different numbers

and sizes of pieces. This might also be related to the type of coating.

Apart from summary statistics, the data were analyzed using analysis of variance (ANOVA) techniques to determine any significant difference between types (Table 2). Standard deviation and mean values were determined as given in Table 3. The results of the individual tests are reported in Table 4 and plotted in Fig. 7. The data obtained is analyzed using SAS, a statistical data analysis software program.

Analysis showed that there is no significant difference in test conditions from one block to another (Table 5). While the mean strength of Type 3 bars was 903 MPa (131 ksi), other types had higher mean strengths, ranging from 979 (142 ksi) to 1014 MPa (147 ksi) (see Table 2). Test results indicate that Types 1, 2 and 4 exhibited similar results while

Table 3
Standard deviations and mean strengths of each type

Type	Standard deviation		Mean	
	(MPa)	(ksi)	(MPa)	(ksi)
1	47	6.8	1007	146
2	22	3.2	1014	147
3	65	9.4	903	131
4	51	7.4	979	142

Table 4
Tensile test results

Test no.	Bar type	Load		Strength	
		(kN)	(Kips)	(MPa)	(ksi)
32	3	130	29	1025	149
6	3	119	27	938	136
27	3	129	29	1015	147
14	4	121	27	953	138
13	3	125	28	983	143
12	3	107	24	843	122
2	1	119	27	939	136
20	3	133	30	1053	153
7	1	124	28	976	142
10	4	119	27	941	136
4	3	131	30	1038	150
19	4	114	26	902	131
26	4	114	26	899	130
9	2	113	25	890	129
5	2	129	29	1022	148
24	4	136	31	1071	155
18	1	130	29	1025	149
29	4	126	28	997	145
3	2	121	27	959	139
23	3	119	27	938	136
28	1	131	29	1034	150
15	2	131	29	1031	149
30	1	129	29	1015	147
1	4	126	28	992	144
17	2	131	30	1036	150
31	2	122	27	962	140
22	2	109	24	859	125
21	1	129	29	1015	147
25	2	126	28	997	145
11	1	129	29	1022	148
8	4	130	29	1025	149
16	1	103	23	815	118

Type 3 is shown to have a mean tensile strength significantly different from the other three. This difference might be related to the type of coating, the only variable considered in this study. Type 3 bars were eliminated from further study because of their low mean strength. Tests for normality were also conducted by using the same software program. Shapiro–Wilk,

Cramer–von Misses [16] and Kolmogorov–Smirnow tests [5,17] were run and all three types showed *P*-value larger than 0.05, which indicates that the results have a normal or an approximately normal distribution (Table 6). The normal probability density function (pdf) estimated to fit the test data is also plotted in Fig. 8. This figure shows the Gaussian distribution representing the tensile strength of the tested bars. The overall mean strength for all types is determined as 990 MPa (142 ksi).

The number of repetitions needed in order to estimate the mean strength within a specified maximum error can be calculated using Eq. (1) for different levels of confidence

$$n = \left(\frac{z_p}{d}\right)^2 \sigma^2 \tag{1}$$

where

- n* number of tests
- d* ± maximum acceptable error for mean strength estimate
- z_p* the 100×*p*th percentile point of a standard normal distribution (100*p* is also the level of confidence that the true mean will lie within estimated mean ± *d*)
- σ* standard deviation. Estimate of *σ* from the represented tests is 45 MPa (6.5 ksi)

For example, to estimate the mean strength with a 95% confidence level, within 5 ksi margin of error, a sample size of at least five rebars are needed. To obtain a 99% level of confidence at the same margin of error, at least nine rebars are needed. The minimum number of test runs needed to obtain 1 or 5 ksi margins of error at various confidence levels are given in Table 7. For the 24 rebars tested, a 5 ksi margin of error translates to an error that is approximately 0.5% of the mean strength. If such an error is acceptable in estimating the mean strength with 99% confidence, then testing a sample of at least nine rebars is recommended.

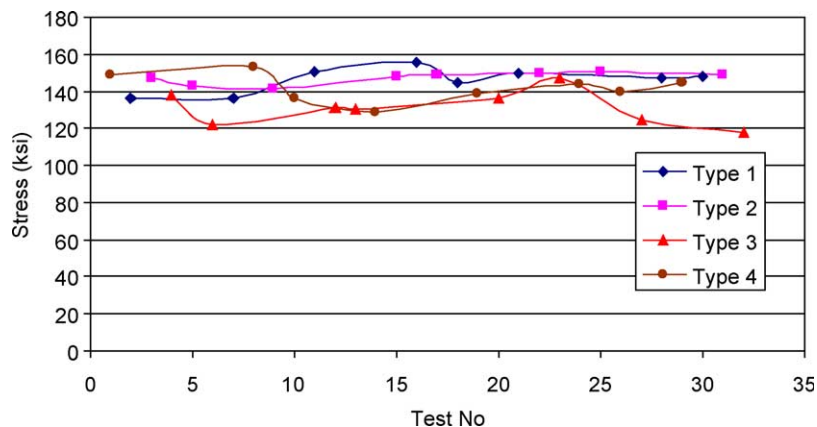


Fig. 7. Test results adjusted for block differences.

Table 5
Block strengths

Blocks	Strength	
	(MPa)	(ksi)
1	983	143
2	955	138
3	964	140
4	970	141
5	980	142
6	1018	148
7	968	140
8	965	140

Table 6
Normality test results

Test	P-value
Shapiro–Wilk	0.8638
Kolmogorov–Smirnov	0.1500
Cramer–von Mises	0.2500

2.6. Conclusions

The following conclusions are drawn based on the test results of this research:

- The test results and the three normality tests show that the Gaussian distribution represents the tensile strength of the population of the tested bars as ACI 440.1R-01 assumes.
- For the samples specifically tested coating might have an effect on the tensile strength of FRP bars. A coating using fillers seems to increase the tensile strength slightly.
- The ANOVA indicates that the three GFRP Types, 1, 2 and 4 have similar tensile strengths.
- Splitting of the fibers is the controlling failure mode of the GFRP bars tested.

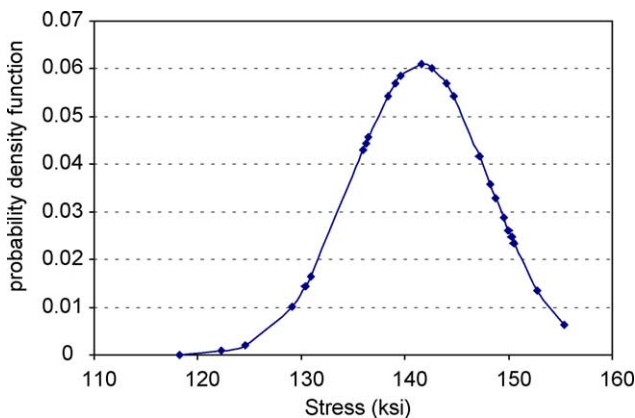


Fig. 8. Distribution of tensile strength.

Table 7
Number of tests to be run for different percentiles and accuracies

	Confidence level							
	90		95		99		99.875	
<i>d</i>	1	5	1	5	1	5	1	5
(ksi)								
<i>n</i>	70	3	116	5	231	9	384	15

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References

- [1] ACI Committee 440. In: Guide for the design and construction of concrete reinforced with FRP bars, 440. 1R-03. Farmington Hills, MI: American Concrete Institute; 2003.
- [2] ACI Committee 440. Recommended test methods for FRP rods and sheets. In: Unpublished draft specifications. Farmington Hills, MI: American Concrete Institute; 2002.
- [3] Non-metallic reinforcement for concrete structures—FRPRCS-5. In: Burgoyne C, editor. Proceedings of International Conference, Cambridge, UK.
- [4] Cosenza E, Manfredi G, Nanni A, editors. Composites in construction: a reality. Proceedings of International Workshop, Capri, Italy. Reston, VA: ASCE; 2001. p. 277.
- [5] Dean A, Voss D. Design and analysis of experiments. In: Springer texts in statistics. New York: Springer; 1999 pp. 122–134.
- [6] De Lorenzis L, Nanni A, La Tegola A. Strengthening of reinforced concrete structures with near surface mounted FRP rods. In: PLAST 2000, Milan, Italy.
- [7] d'Hooghe EL, Hoek B, Edwards CM. Applications for FULCRUM* thermoplastic composite technology. In: Fifth World Pultrusion Conference, Berlin, Germany.
- [8] Faza SS, GangaRao HVS. Glass FRP reinforcing bars for concrete. In: Fiber reinforced (FRP) reinforcement for concrete structures: properties and applications. In: Developments in civil engineering, vol. 42 pp. 167–188.
- [9] Figueiras J, Juvandes L, Furia R, editors. Composites in construction. Proceedings of CCC 2001, Porto, Portugal.
- [10] Lopez-Anido R, Karbhari VM. Fiber reinforced composites in civil infrastructure. In: Emerging materials for civil infrastructure, state-of-the-art. Reston, VA: ASCE; 2000 pp. 41–78.
- [11] Micelli F, Nanni A. Mechanical properties and durability of FRP rods. In: CIES Report 00-22. Rolla, MO: University of Missouri-Rolla; 2001 pp. 15–20.
- [12] Murphy J. In: Reinforced plastics handbook. Amsterdam: Elsevier; 1998.
- [13] Nanni A, editor. Fiber-reinforced-plastic (FRP) reinforcement for concrete structures: properties and applications. Developments in civil engineering, vol. 42. Amsterdam: Elsevier; 1993. p. 450.

- [14] Nanni A, Dolan CW, editors. FRP reinforcement for concrete structures. Proceedings of International Symposium, ACI SP-138. Detroit, MI: American Concrete Institute; 1993. p. 977.
- [15] Neale KW, Labossiere P, editors. Advanced Composite Materials in Bridges and Structures. Proceedings of Canadian Society for Civil Engineering, Montreal, Canada, 1992. p. 750.
- [16] Shapiro SS, Wilk MB, Chen HJ. A comparative study of various tests for normality. *J Am Stat Assoc*, Monte Carlo 1968;1343–72.
- [17] Shapiro SS. How to test normality and other distributional assumptions. Teng, J.-G., editor. FRP Composites in civil Engineering. Proceedings of CICE, Vol. 1&2. Hong Kong: 2001. *J Am Soc Quality Control*, Milwaukee, WI 1980.
- [18] Tumialan GJ, Galati N, Namboorimadathil SM, Nanni A. Strengthening of masonry with FRP bars ICCI 2002, San Francisco, CA 2002.
- [19] White TD, editor. Composite materials and structural plastics in civil engineering construction. Proceedings of the Materials Engineering Congress. New York: American Society of Civil Engineers; 1992. p. 532–718.