Performance of glass fiber-reinforced polymer reinforcing bars in tropical environments - Part 1: Structural scale tests

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Performance of Glass Fiber-Reinforced Polymer Reinforcing Bars in Tropical Environments—Part I: Structural Scale Tests

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A set of accelerated aging and natural environment tests has been carried out to evaluate performance of glass fiber-reinforced polymer (GFRP) reinforcing bar in a tropical environment. Beams were cast with the GFRP reinforcing bars as internal reinforcement. They were immersed in a 60 °C water bath for varying durations. The novelty of the experiment was that the environmental exposure was given to the beams while they were subjected to service loads. These loads kept the cracks open for reinforcing bars to remain exposed to hot water. Thus, a field environment very similar to a tropical climate was created. The loaded specimens were also subjected to natural weathering for 18 and 30 months duration. The reinforcing bars were removed from the specimens and investigated at both structural and microstructural scale to assess the degradation, if any. In the first part of the paper, the structural level studies are discussed. In Part 2, the microstructural investigation is reported.

Keywords: carbon; glass fiber-reinforced polymer; reinforcing bars.

INTRODUCTION

Carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) have been used as an alternative to steel in concrete due to high strength-to-weight ratio, high stiffness-to-weight ratio, and corrosion and fatigue resistance. GFRPs have been found attractive in the Asian region due to their cost competitiveness in comparison to CFRP. Some literature is available on structural application of GFRP reinforcing bars.[1-4] Wide-spread use of fiber-reinforced polymers (FRPs) in construction is hampered in this part of world due to lack of long-term durability and performance data, especially in a tropical environment.

The main environmental factors for the deterioration of GFRP are temperature, sunshine, water/moisture, alkalinity, and load. Most of the early durability tests were carried out with reference to application of FRPs in aerospace. Thus, considerable data is available with only one or a combination of some of these parameters. The effect of water/moisture on the mechanical properties of FRPs is well known.[5] Recently, durability tests have been carried out for application in structural engineering, and these point to susceptibility of glass fibers to alkali attack.[6-14] For GFRP embedded in moist concrete under various sustained stress levels, three types of stress corrosion mechanisms have been identified: stress, crack propagation, and diffusion.[7] Researchers report degradation of the reinforcing bar varying from 4.9 to 100%, depending on the parameters selected for durability tests, namely alkalinity, temperature, stress, and duration of the tests. The results are summarized in Table 1. The faster deterioration of the stressed specimens indicates that the resin cracking also plays a significant role in the degradation of GFRP in addition to alkalinity. Efforts are being made to compile data and provide a basis for design codes.[15]

The objective of the present investigation is to evaluate durability-related performance parameters of one type of GFRP reinforcing bar in concrete. The methodology of the experiments presented in this paper has been very close to the actual field conditions in tropical regions. ACI 440.1R-03 recommends the test methodology for long term performance of FRP in concrete.[16] The following points along with ACI 440.1R-03 were considered in the experimental study.

- The GFRP reinforcing bars are embedded in concrete, as in actual structural applications;
- The reinforcing bars were used as tension reinforcements in bending members as envisaged in use;
- Concrete was moist or wet as in tropical regions;
- GFRP composite samples underwent exposure stress levels that would be seen in service;
- The synergistic effects of stress level, moisture, temperature, and alkalinity were considered;
- Elevated temperatures were used for accelerated testing. These temperatures, however, did not exceed the glass transition temperature of the resin, nor did the temperature induce any different damage conditions. In the experiment the temperature was 60 °C, and
- Accelerated test procedures need to produce effects at the matrix and interphase levels, in addition to those at fiber level. Cracks were introduced in the concrete beam exposing reinforcing bars and they were kept open by maintaining service loads on them during the exposure.

RESEARCH SIGNIFICANCE

GFRP is predicted to have great potential use as reinforcement in concrete; in practice, it has started to get a hold in the tropical region. The use of GFRP reinforcing bar in construction is hampered by lack of long-term durability and structural performance data. In this paper, concrete GFRP beams have been simultaneously subjected to stress and alkaline environment, as well as temperature and humidity of the tropics. Structural scale behavior such as load-deflection and durability has been studied in Part 1. In Part 2, microstructural scale tests that assess the nature, quantum, and mechanism of degradation are reported.

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EXPERIMENTAL PROGRAM

Concrete mixture

The grade of concrete used was M30, which had a characteristic strength of 30 MPa. Grade 43 ordinary portland cement, having a minimum 43 MPa compressive strength at 28 days, was used. No additives or high-range water-reducing admixtures were used. Compaction was done using a needle vibrator. Aggregate-to-cement ratio, water-cement ratio (w/c), and ultimate compressive strength are given in Table 2.

Reinforcement characteristics

Commercially available E-glass/vinylester GFRP reinforcing bars were used. The cross section of the reinforcing bar was 70.97 mm^2 having tensile strength of 700 MPa and elastic modulus of 40.7 GPa (Fig. 1). The bar surface had a helically-wrapped E-glass tow and sand coating for bond enhancement.

Specimens

The specimens consisted of 90 mm-wide, 180 mm-deep, and 1800 mm-long plain concrete beams. The effective span was 1700 mm. The beams were reinforced with a single GFRP reinforcing bar with a clear cover of 30 mm. All the beams after casting were cured at normal temperature in a water bath for 28 days. The support points were located at 50 mm from the ends of the beam to accommodate the support system. The cross-section and nomenclature is given in Fig. 2.

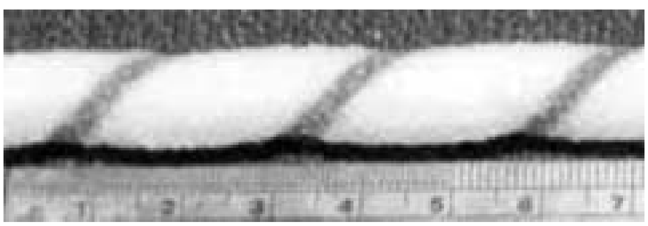

Fig. 1—E-glass/vinylester GFRP reinforcing bar with helical tow.

Service loading

To load the beams, a spring-bracket assembly was fabricated (Fig. 3). The assembly consisted of clamps made of steel channel sections, long threaded bolts with nuts, and springs. The springs had a 60 mm external diameter, a 200 mm unloaded length, and a stiffness value of 77 N/mm. The springs were calibrated by using a proving ring and their

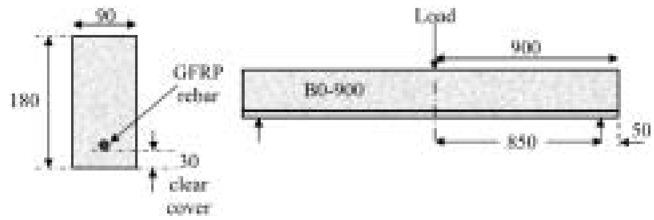

Fig. 2—Cross section and nomenclature (B0-900). (Note: dimensions in mm.)

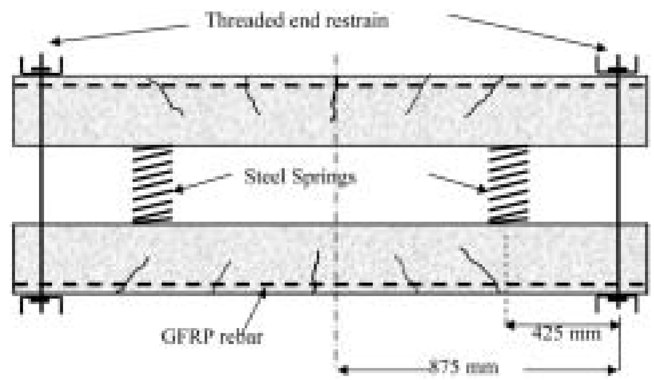

Fig. 3—Spring-bracket assembly for sustained load on GFRP-reinforced beams 1800 mm long.

Table 1—Loss of tensile strength in unstressed and stressed GFRP composites

Series no.	Type	Stress, %	Conditioning	Duration, days	Loss, %	Reference
1	GFRP reinforcing bars	0	Embedded in concrete beam and conditioned in tap water at 40 °C	120	4.9	6
		0	Embedded in concrete beam and conditioned in sea water at 40 °C	120	10.3	
		20 to 25	Embedded in concrete beam and conditioned in tap water at 40 °C	120	27.9	
		20 to 25	Embedded in concrete beam and conditioned in sea water at 40 °C	120	27.8	
2	GFRP reinforcing bars	30	13.1 pH solution at 22 °C	60	22	7
3	GFRP reinforcing bars	20% service load	Embedded in concrete beam and conditioned at 12.5 pH $Ca(OH)_2$ solution at 60 °C	60	19.6	8
			Embedded in concrete beam and conditioned in lab air	180	19.6	
4	GFRP composite	0	5-molar NaOH solution at 60 °C	150	73	9
5	GFRP reinforcing bars	0	12.6 pH solution at 60 °C	21	30	10
				42	40	
6	GFRP rods	0	Embedded in low-heat high-performance concrete (LHHPC) and normal conventional concrete (NCC) and submerged in water bath at 60 °C	730	36 to 53	11
7	GFRP rods	0	12 pH solution at 25 °C	180	25	12
			12 pH solution at 60 °C	180	28.6	
8	GFRP rods	0	High alkalinity (13.5 pH) at room temperature	270	63	13
		10	High alkalinity (13.5 pH) at room temperature	270	70	
		25	High alkalinity (13.5 pH) at room temperature	25	100	

linearity was ensured for the entire load-deflection zone. The beams were placed back to back, with springs placed at a distance of 425 mm from the brackets. The loads were controlled by regularly monitoring the spring length while tightening the bolts.

Accelerated environmental conditioning

Bending cracks were introduced in the beams by subjecting them to 50% of ultimate load, using the spring-bracket assembly. The ultimate load was experimentally validated with a pilot test. The beams were then unloaded to 20% of the ultimate load to simulate service load conditions and to keep the cracks open. The purpose of introducing cracks was to expose the reinforcing bars to the environment. A steel tank 1.2 m wide, 1 m deep, and 2.4 m long was fabricated to accommodate six loaded specimens at a time. The heating system was designed to maintain water at 60 °C ± 0.1 °C. The loaded specimens were kept in water tank at 60 °C for duration of 3, 6, and 12 months. The water in the tank was periodically changed with tap water and the pH of the water in the tank never exceeded 8.5.

Natural environmental conditioning

The beams were conditioned under service loads for natural weathering outdoors for 18 and 30 months in the industrial city of Mumbai (Bombay, India). The area experiences sunny weather for 9 months per year with temperatures varying from 10 to 38 °C. For 3 months of the monsoon season, the area experiences one of the highest rainfalls in the country. In general, the environment is hot and humid.

Loading scheme and designation of test beams

The conditioned beams have been tested in bending with three-point loading. This simulates flexural tension in the reinforcing bar in contrast to standard pull out tests. The loading positions varied progressively from the center of the beam toward the support at an interval of 200 mm. This was done to study the performance of beams under the combined effects of bending and shear. The beam section was designed to fail in compression in concrete rather than tension in the GFRP reinforcing bars. The beams were loaded at center at a distance of 900 mm from the edge of the beam. Subsequently, for other beams, the load position was changed to 700, 500, and 300 mm. The beams were designated as per loading position and duration of conditioning. The nomenclature is in Table 3. A special loading frame was fabricated to load the beams eccentrically as the available universal testing machines could only load the beams centrally.

EXPERIMENTAL RESULTS

First cracking and ultimate failure load/moment

In the first set of tests, gradual loads were applied until failure. The support point was 50 mm from the end of the beam resulting in a moment arm of 850, 650, 450, and 350 mm, respectively, from the support. The results of tests conducted on the four beams are in Table 4.

Load-deflection characteristics

The displacements of the beams were measured using three linear voltage differential transducers (LVDTs) having a travel of 50 mm and resolution of 0.01 mm. The maximum deflections at failure are presented in Table 5. A load cell of 250 kN capacity was used to measure the loads. The load and displacement results were acquired using a data card and transferred to the computer data files. The load-deflection characteristics of the tested beams are given in Fig. 4 to 7, respectively.

It may be noted that the ultimate loads of the conditioned beams were always higher than those of the fresh beams. The ultimate deflections of the conditioned beams were also higher in all other cases except the B-900 series. The reasons for higher ultimate load and ultimate deflection are discussed later in the paper.

Slip of reinforcing bar

It has been reported earlier that GFRP reinforcements tend to slip in bond.[8] To measure the bond slip, LVDTs were placed at the two ends of the GFRP reinforcing bars. The difference of the readings of LVDTs gives the actual slip/relative displacement with reference to concrete (Table 6). The slip in the fresh beams was negligible. The slip increased in conditioned beams. It was at a maximum in the beams under natural environment. However, there was no failure due to bond slip in any of the specimens.

Table 2—Mixture design of concrete

Mixture	*a/c* (by volume)	M1: M2: FA: 20 mm 10 mm sand, by volume	*w/c* (by volume)	f'_c, MPa
M30	4.72	25: 30: 45	0.44	33.9

Note: *a/c* = aggregate-cement ratio; M1, M2 = coarse aggregates; FA = fine aggregate; *w/c* = water-cement ratio; and f'_c = ultimate compressive strength.

Table 3—Designation of beams

Series no.	Designation	Conditioning	Load position from support, mm
1	B0-900, B0-700, B0-500, B0-300	B0 → 0 months	850, 650, 450, 250
2	B3-900, B3-700, B3-500, B3-300	B3 → 3 months in tank at 60 °C	850, 650, 450, 250
3	B6-900, B6-700, B6-500, B6-300	B6 → 6 months in tank at 60 °C	850, 650, 450, 250
4	B12-900, B12-700, B12-500, B12-300	B12 → 12 months in tank at 60 °C	850, 650, 450, 250
5	B18A-500, B18A-300	B18A → 18 months outdoor	450, 250
6	B30A-500, B30A-300	B30A → 30 months outdoor	450, 250

Table 4—Ultimate failure moments of GFRP beams

Beam designation	Moment arm, mm	Experimental results			
		Load at first crack, kN	Ultimate load, kN	Ultimate moment, kN·m	Ultimate shear, kN
B0-900	850	3.5	10.27	4.37	5.13
B0-700	650	4.0	11.3	4.53	6.97
B0-500	450	4.5	13.2	4.37	9.71
B0-300	250	8.0	18.5	4.00	15.55
Pilot test	450	5.0	12.68	4.2	9.32

Table 5—Maximum deflection of original beams

Beam designation	Moment arm, mm	Maximum deflection, mm
B-900	850	25.72
B-700	650	20.76
B-500	450	17.3
B-300	250	12.6
Pilot test	450	17.62

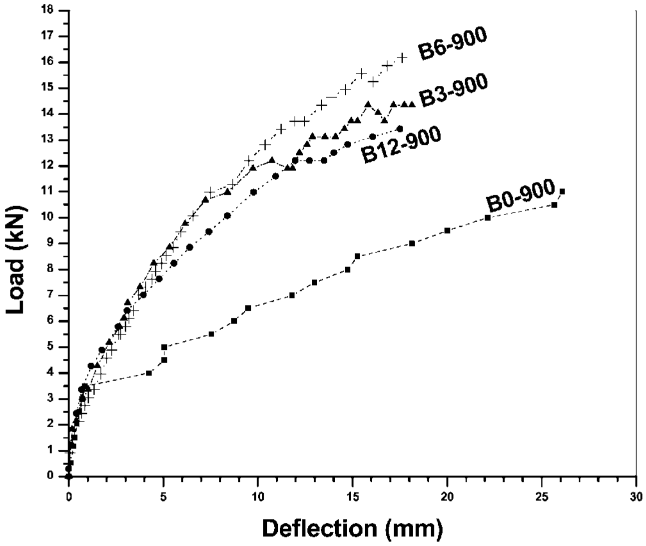

Fig. 4—Load-versus-deflection characteristics of beams loaded centrally (B0-900, B3-900, B6-900, and B12-900).

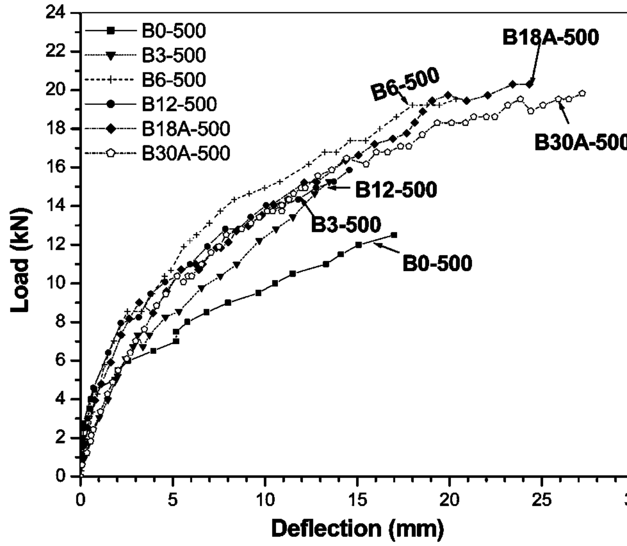

Fig. 6—Load-versus-deflection characteristics of beams loaded at 450 mm from support (B0-500, B3-500, B6-500, B12-500, B18A-500, and B30A-500).

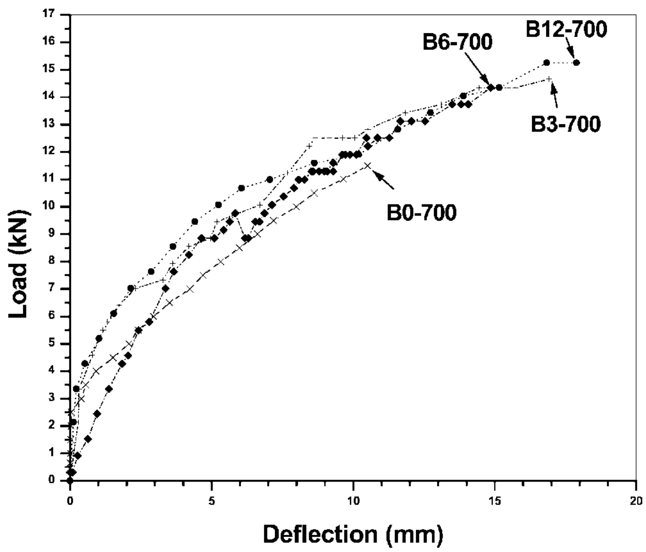

Fig. 5—Load-versus-deflection characteristics of beams loaded at 650 mm from support (B0-700, B3-700, B6-700, and B12-700).

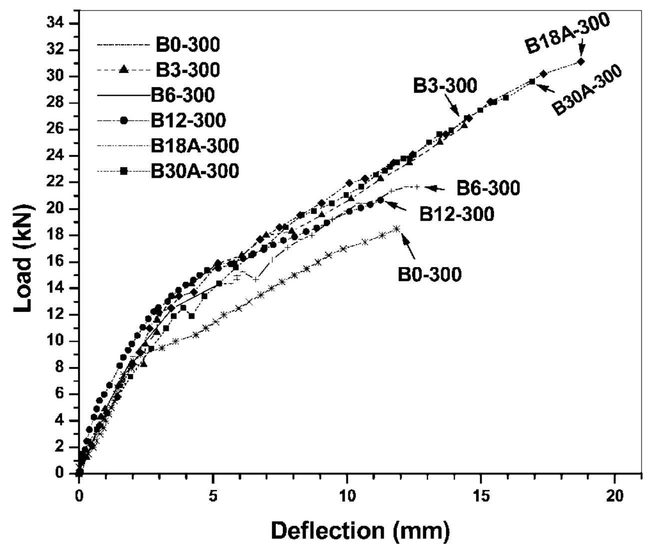

Fig. 7—Load-versus-deflection characteristics of beams loaded at 250 mm from support (B0-300, B3-300, B6-300, B12-300, B18A-300, B30A-300).

Fig. 8—Shear crack meeting vertical flexural crack below load at failure in Specimen B0-900.

Crack pattern

Test specimens—The beams (B0-900) failed due to compressive failure of concrete. GFRP reinforcing bars remained intact. Initially, the cracks developed in the middle portion of the beams and were vertical. As load was gradually increased, the vertical cracks changed to diagonal cracks, and only when these crack progressed and coalesced did the final failure take place (Fig. 8). This mode of failure has remained the same for all the specimens when the loading point is shifted towards the support. No bond failure of the reinforcing bar was observed.

Conditioned specimens—The mode of failure changed when the specimens were conditioned. There was substantial reduction in the number of cracks formed. One major crack under load opened and divided the beam into two fairly rigid parts. The failure of all conditioned beams was through the failure of GFRP reinforcing bars. The failure was abrupt, that is, they failed without any warning in terms of steadily widening cracks or excessive deformation. One set of failed specimens is shown in Fig. 9. This behavior was contravened to the fresh beams.

The reinforcing bars failed in beams that were subjected to outdoor natural weathering but showed substantially higher slip behavior than the fresh beams or indoor conditioned

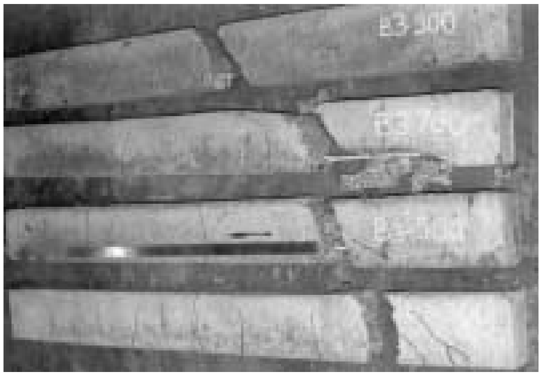

Fig. 9—Failed specimens B3-900, B3-700, B3-500, and B3-300 with GFRP reinforcing bar.

beams. Wider cracks developed before failure in comparison to conditioned beams.

The highlights of the test are:

- All conditioned beams failed at a higher ultimate load in comparison to the fresh beams;
- All conditioned beams deflected more than the fresh beams. The exceptions were centrally loaded beams. Original beam B0-900 deflected maximum of 26.11 mm in comparison to deflections of B3-900, B6-900, and B12-900, which are 18.14, 17.63, and 17.51 mm;
- All conditioned beams failed due to failure of GFRP reinforcing bars. In all fresh beams, the concrete failed and reinforcing bars remained intact at failure; and
- Maximum bond slip was in beams under natural conditioning. However, no failure due to bond slip took place.

The increase in ultimate load and ultimate deflection in beams due to conditioning was heartening. The changes in the failure mode, however, led to the testing of the constituent materials along with the reinforcing bars.

Testing of conditioned concrete

Compression—Twenty concrete cylinders were cast and kept in the tank at 60 °C for 1, 3, 6, and 9 months. The concrete was tested for the effect of accelerated aging on stress-strain behavior.[17] The results are listed in Table 7. The average cube strength was 38.3 MPa. The stress versus strain plot of the tested specimens is shown in Fig. 10. The concrete gained strength with time. The strength gain was approximately 22% for nine months. The ultimate strain, however, had a decreasing trend with time. The elastic constant increased with time of exposure. This is due to hydration of cement at higher temperature in presence of moisture.

Tension—Split tensile tests were conducted on standard cylinder specimens on a compression testing machine as per standards.[18-20] Line load on the cylinder specimen in the horizontal position was applied and the failure load at which the cylinder split into two halves about the vertical diametrical plane was noted. The test was repeated for three specimens and the average tensile strength was calculated and recorded in Table 8. There was an 85% increase in the tensile strength of concrete in 9 months due to accelerated ageing. It is expected that the flexural modulus of concrete will also increase in the same proportion.

The increase in failure load capacity of the conditioned beams may be due to the increase in the capacities in the concrete. The focus, however, is in the condition of the reinforcing bars. Although there were increases in load capacities of the beams, there was a marked difference in the crack patterns in the beams. While the unconditioned beams had many cracks, the conditioned beams had one major crack until failure. To investigate this point the bar forces were estimated using a numerical model.

Table 6—Slip/relative displacement of GFRP reinforcing bars in concrete beams

Series no.	Types of beams		Slip/relative displacement, mm
1	Original beams	B0-900	Negligible
2		B0-700	Negligible
3		B0-500	Negligible
4		B0-300	Negligible
5	Conditioned beams in tank	B3-900	0.04
6		B3-700	0.23
7		B3-500	0.39
8		B6-900	0.04
9		B6-700	0.7
10		B6-500	0.3
11		B6-300	0.5
12		B12-500	0.3
13	Outdoor-weathered beams	B18A-500	1.77
14		B18A-300	0.31
15		B30A-500	0.63
16		B30A-300	0.35

Table 7—Effect of conditioning at 60 °C on concrete strength

Series no.	Curing duration	Specimen	Failure stress		Failure strain	
			Individual	Average	Individual	Average
1	28 days in water	Cylinder a	32.82	31.68	0.00158	0.00189
		Cylinder b	31.689		0.002	
		Cylinder c	30.55		0.00208	
2	1 month at 60 °C	Cylinder a	31.689	33.95	0.0018	0.00171
		Cylinder b	35.08		0.00187	
		Cylinder c	35.08		0.00147	
3	3 months at 60 °C	Cylinder a	35.085	37.38	0.00128	0.00132
		Cylinder b	37.45		0.00135	
		Cylinder c	39.61		0.00132	
4	6 months at 60 °C	Cylinder a	32.82	35.08	0.00131	0.00135
		Cylinder b	36.21		0.00139	
		Cylinder c	36.21		0.00135	
5	9 months at 60 °C	Cylinder a	37.35	38.48	0.00128	0.00133
		Cylinder b	38.48		0.00131	
		Cylinder c	39.61		0.0014	

Table 8—Split tensile strength of concrete

Series no.	Sample description	Tensile strength f_t, MPa	Percentage change
1	Cylinder at 28 days	2.037	—
2	Cylinder conditioned for 9 months in tank at 60 °C	3.763	+84.7

NUMERICAL MODEL AND RESULTS

Based on the experimentally-observed stress-strain behavior of concrete and GFRP reinforcing bar, a numerical model is developed to estimate the stresses in concrete and GFRP reinforcing bar at different load levels.[21] The following assumptions have been made:

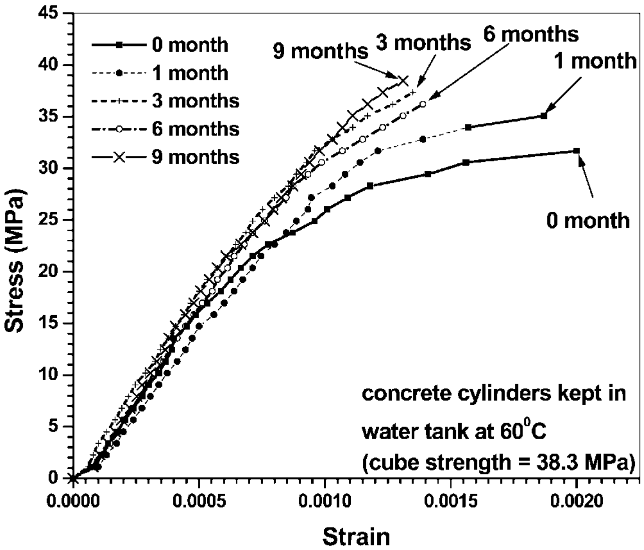

Fig. 10—Stress-versus-strain plot of concrete cylinders conditioned in water tank at 60 °C.

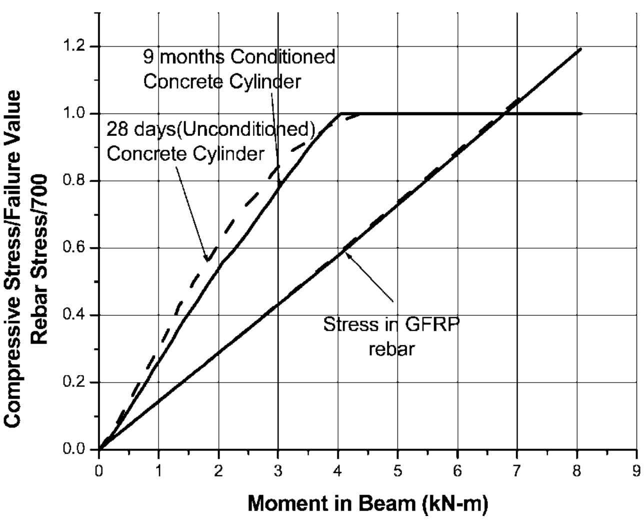

Fig. 11—Stresses in concrete and reinforcing bar corresponding to moment in beam.

- Strain varies linearly along the depth of the beam; and
- The tensile strength/flexural modulus of the concrete is negligible

With these assumptions, the neutral plane depth can be calculated by applying the conditions of equilibrium along the axis of the beam. The stress-strain relation of the conditioned and unconditioned cylinders of Fig. 10 is used to evaluate stresses in concrete and reinforcing bars at any stage of loading in the specimen section. The maximum plastic strain in concrete assumed is 0.0035. The resultant bending moment is calculated by applying moment equilibrium condition about the neutral plane.

The unconditioned beam B0-900 failed at 4.37 kN·m. The compressive stress in concrete reached its ultimate failure value. Based on the theoretical model, the stress in reinforcing bar was 62% of its strength (Fig. 11). The conditioned beam B12-900 failed at 5.07 kN·m. The stress in the reinforcing bar was 73% (Fig. 11). Reinforcing bar rupture, however, was observed in all conditioned beams. This indicates that there may be degradation of the strength of the reinforcing bars due to conditioning. At this point it was decided to investigate the conditioned reinforcing bars by digging them out of the beam.

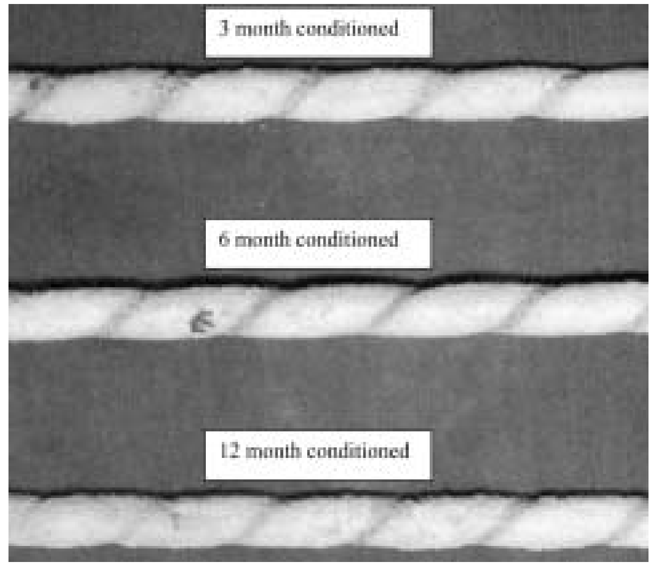

Fig. 12—Removed GFRP reinforcing bars from conditioned concrete beams.

TEST OF CONDITIONED REINFORCING BARS

The GFRP reinforcing bars were removed from the conditioned specimens and were checked for their material properties including tensile strength and modulus of elasticity.[22] To compare the results, a set of reinforcing bars were conditioned in the tank along with the beams and tested along with the removed reinforcing bars. Utmost care was taken to avoid any damage to the reinforcing bars while removing them. On visual inspection, it was found that there was little visible surface degradation. When water was dropped on the conditioned reinforcing bars, however, it was absorbed very quickly. This indicated that there might be microstructural changes in the reinforcing bars. All the reinforcing bars removed from the beams conditioned at 60 °C for 3, 6, and 12 months are shown in Fig. 12. The GFRP reinforcing bars were tested by a universal testing machine. Special end grips of 30 mm diameter and 150 mm length were prepared for testing reinforcing bars. For preparing special grips, epoxy with sand was used. Special arrangement was made to keep the bar at the center of the grips.

The results of the tensile tests are listed in Table 9 and 10, respectively. The original reinforcing bar failed in typical broom shape due to individual fiber fracture over a large length of the reinforcing bar. The conditioned reinforcing bars, however, failed at a lesser load and failure mode was different from the original reinforcing bar. The failed specimens are shown in Fig. 13 and 14, respectively.

Due to accelerated ageing, GFRP reinforcing bars lost their tensile strength by 42.2, 55.7, and 65.0% in 3, 6, and 12 months of conditioning (Table 9). The reinforcing bars in beams conditioned outdoors for 18 and 30 months lost their tensile strength by 34.6 and 38.6% (Table 9). The GFRP reinforcing bars directly kept in tank at 60 °C for 1, 3, 6, and 9 months lost their tensile strength by 32.0, 43.6, 53.7, and 57.7%. Even though the damage to fibers was high due to conditioning, the change in the modulus of elasticity was only around 6% (Table 10). To investigate this point, the

Table 9—Comparative study of tensile properties of GFRP reinforcing bars

Case	Ultimate tensile strength	
	Mean, MPa	Percentage decrease
Nominal value of original reinforcing bar (manufacturer's specification)	700	—
Tested after 2 years kept in lab	639.7	8.6
3 months at 60 °C in water tank (cut out from beam)	405.8	42.2
6 months at 60 °C in water tank (cut out from beam)	309.9	55.7
12 months at 60 °C in water tank (cut out from beam)	245.17	64.98
18 months outdoors (cut out from beam)	458	34.6
30 months outdoors (cut out from beam)	429.8	38.6
1 month at 60 °C (kept open in tank)	476.2	31.97
3 months at 60 °C (kept open in tank)	394.5	43.6
6 months at 60 °C (kept open in tank)	324	53.7
9 months at 60 °C (kept open in tank)	296	57.7

Table 10—Comparative study of elastic modulus of GFRP reinforcing bars

Case	Elastic modulus	
	Mean, MPa	Percentage change
Nominal value of original reinforcing bar (manufacturer's specification)	40.79	—
Tested after 2 years kept in lab	43.1	+5.6
6 months at 60 °C in water tank (cut out from beam)	40.8	+0.02
9 months at 60 °C (kept open in tank)	38.85	–4.75

micro-structural study of reinforcing bars was carried out. This will be reported in the second part of the paper.

Even though reinforcing bars lost their tensile strength progressively with accelerated ageing, the load carrying capacity of beams increased up to 6 months of curing and then it decreased (Fig. 4). This can be attributed to the increase in the flexural modulus of concrete due to curing in presence of water and the raised temperature. The increase in the flexural modulus is proportional to the split tensile strength, which went up by 85% in 9 months (Table 8). Furthermore, the ratio of area of concrete to reinforcing bar is very large, that is, 227:1. Therefore, the concrete in both the compression and the tension zones contributes considerably to the strength of the beams. As a result, the conditioned beams took higher loads even though the reinforcing bars degraded considerably. However, the failure shifted from the compression zone of the concrete to reinforcing bar fracture. The numerical model neglects the tensile strength of the concrete. Therefore, although there was a close agreement of the experimental results with that of the numerical model in the case of fresh beams, the model failed to predict the shift in the failure location. Consequently, the numerical prediction diverged from the experimental observation.

DURABILITY OF GFRP REINFORCING BARS

The results of tensile tests on conditioned reinforcing bars from Table 9 are plotted in Fig. 15. Due to accelerated ageing, GFRP reinforcing bar lost its tensile strength exponentially up to 65% of the original value in 12 months (Fig. 15). Ultimate tensile strength of reinforcing bar was plotted against accelerated ageing time in log scale (Fig. 16). Failure stresses for outdoors

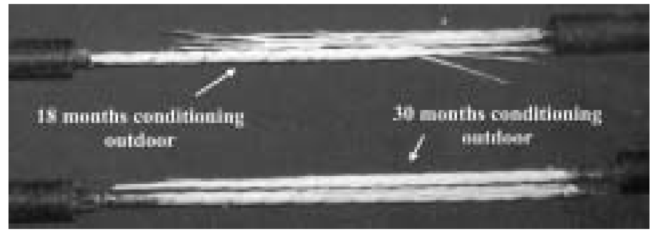

Fig. 13—Failure of GFRP reinforcing bars in typical broom shape.

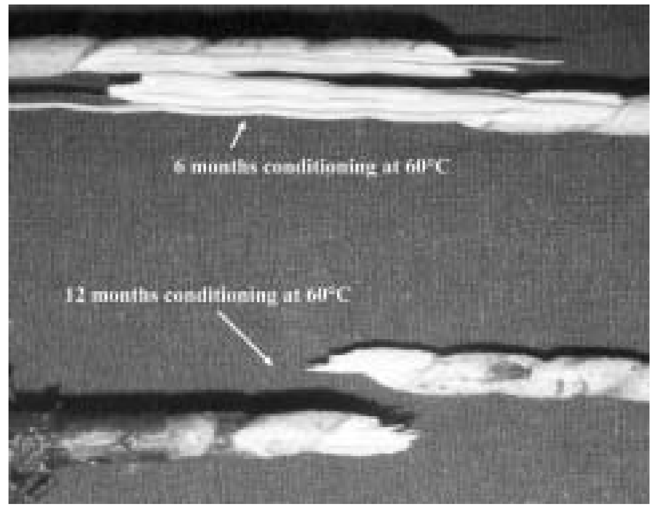

Fig. 14—Failed specimen of conditioned GFRP reinforcing bars.

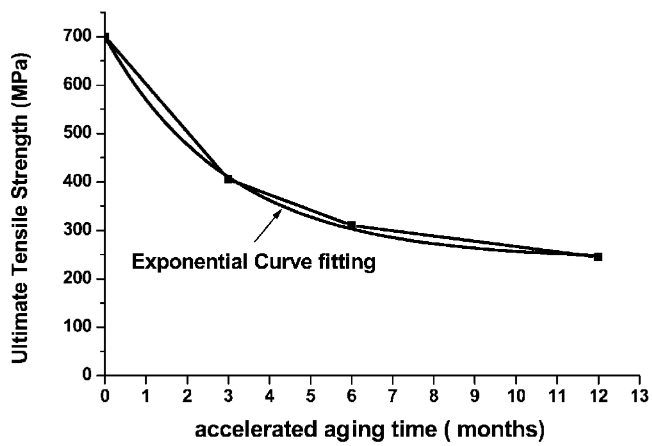

Fig. 15—Effect of accelerated aging on GFRP reinforcing bar strength in beams.

results of 18 and 30 months are plotted on the same graph and the corresponding accelerated ageing times were determined. Based on these results, the accelerated age of GFRP reinforcing bar was interpolated for the expected field life in years. Three, six, and 12 months of accelerated aging in a water tank at 60 °C correspond to 8, 16, and 32 years of deterioration in the natural environment (Fig. 17). The interpolation is based on field data of 12 and 18 months. More data over several years are required for a more accurate estimate. This is a future endeavor.

SUMMARY AND CONCLUSIONS

The primary aim of the investigation was performance of GFRP reinforcing bar reinforced beams. All the fresh beams

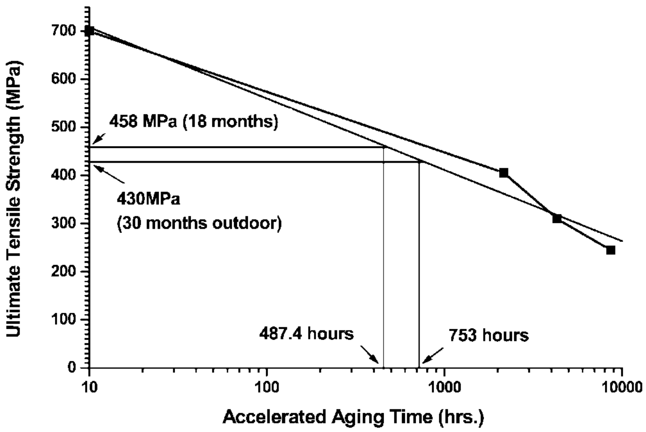

Fig. 16—Extrapolation of accelerated aging with respect to outdoor conditioning.

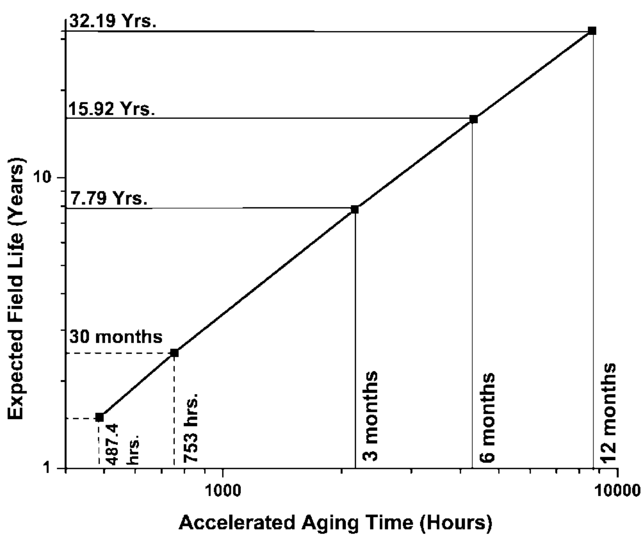

Fig. 17—Relation between accelerated aging and expected field life based on 18- and 30-month field data.

behaved as expected, that is, the concrete failed in compression and the reinforcing bars remained intact. No slip behavior was observed. Wide and distributed cracks were observed at failure. The mode of failure of the beams, however, changed after they were conditioned under a simulated tropical climate. All conditioned beams withstood a higher load than the fresh beams. The increase was around 50%. In all the beams except the centrally loaded ones, the ultimate deflections increased with conditioning. The increase was approximately 40% in beams conditioned in a natural environment. The average stiffness of the beam was variable. All beams, however, showed an increase in stiffness due to conditioning. But there was marked change in the failure mode. In contrast to a large number of well-distributed cracks, there was one major crack under the load that led to failure. Moreover, the reinforcing bars of all the conditioned beams ruptured.

The tests on constituent materials showed that the concrete gained substantial strength due to conditioning in the tank at 60 °C. The compressive strength increased by 22%. The split tensile strength increased by 85%. The elastic modulus increased by 21%. This is primarily due to accelerated hydration of cement in concrete due to moisture and temperature. The testing of reinforcing bars dug out of the conditioned beams revealed that GFRP reinforcing bars lost their strength by 42.2, 55.7, and 65% in 3, 6, and 12 months of accelerated conditioning. Even due to natural weathering they lost their strength by 34.6 and 38.6% in 18 and 30 months. In contrast, the change in elastic modulus was only 6%. The dual effect of increase in strength of concrete and decrease in strength of the reinforcing bars is the cause of changes in the failure mode of conditioned beams. Due to the increase in the strength of concrete, the failure loads were higher in the conditioned beams. The stiffness of the reinforcing bar did not change appreciably. As a result, the stiffness of the beam went up. The strength of the reinforcing bar, on the other hand, reduced considerably. This led to the shift in failure mode from concrete rupture to reinforcement rupture. Conditioning has affected the slip of reinforcing bars in conditioned beams. The slip of reinforcing bars, however, was not significant both for conditioned and unconditioned beams.

Despite the use of vinylester as a matrix, the reinforcing bars degraded substantially due to the synergistic effect of heat, moisture, stress, and alkali. Based on the data available, it can be extrapolated that the reinforcing bars lose their strength by 65% in a service life of 32 years. This observation is based on limited data available at this point and requires more tests of longer duration to substantiate. The methodology can be used to predict the long term behavior of GFRP reinforced beams in terms of years. More tests with different temperatures, alkalinity, and prestressing stresses are required to build a model to predict the rate and quantum of damage to the fibers. Micro structural studies have been carried out to identify the degradation in the reinforcing bars. The results of this study are presented in Part 2.

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