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LONG TERM BEHAVIOR OF GFRP REINFORCED CONCRETE BEAMS IN HARSH ENVIRONMENT

Mohamed A. Safaan

Civil Engineering Department, Faculty of Engineering
Menoufyia University, Egypt

ABSTRACT

The long-term and durability performance of concrete beams reinforced with conventional steel *and GFRP bar reinforcement in a harsh environment* and under sustained load was investigated. Three simply supported beams (100x250x2700 mm) were reinforced using in-house manufactured GFRP bars and stirrups, while three beams (100x200x2700 mm) were reinforced with high tensile deformed steel bars. One beam in each category was tested under four point loading to determine the initial flexural capacity. The second beam was tested under a uniformly distributed sustained load in the laboratory atmosphere, while the third was further subjected to wet/dry cycles and salt solutions. The results of monitoring the tensile and compressive strains, mid-span deflection and cracking over a period of one year are presented. Signs of steel corrosion in the form of longitudinal cracks and increased tensile strains have been observed after 31 weeks in the prescribed harsh environment, while no damage *was observed in the similar GFRP reinforced* beam.

يتناول هذا البحث دراسة سلوك الكمرات الخرسانية المسلحة بأسياخ وكانات مصنعة معمليا من البوليمرات المسلحة بالألياف الزجاجية علي المدى الطويل تحت تأثير أحمال التشغيل. تم اختبار الكمرات في ظروف بيئية عادية وفي بيئة قاسية تعرضت فيها الكمرات لدورات من الرطوبة والجفاف والمحاليل الملحية. تم رصد التشكلات الحادثة بالكمرات متضمنة الترخيم والانفعالات، ومتابعة حدوث الشروخ وامتدادها نتيجة للزحف والانكماش. تم مقارنة السلوك الانشائي لهذه الكمرات بسلوك كمرات مماثلة مسلحة بصلب التسليح التقليدى؛ حيث أوضحت النتائج إمكان حدوث صدأ حديد التسليح التقليدي خلال واحد وثلاثين أسبوعا من بدء الاختبار في البيئة القاسية، بيمنا أبدت الكمرات المسلحة بالأسياخ البولمرية أداء جيدا تحت نفس الظروف.

Keywords: *GFRP bars, RC beams, long-term, durability, crack width, deflection.*

1. INTRODUCTION

Fiber reinforced polymer (FRP) composites have been successfully used in non-structural applications for years. Their use in civil infrastructure applications in the form of external and internal concrete reinforcement is relatively new. Reported applications included the use of FRP rebars, wraps for seismic retrofit of columns and externally bonded composites for strengthening different structural elements. Basically, the use of FRP composites in such applications is due to the high durability of these materials compared to conventional reinforcement. However, the environmental effects *that are considered critical* for the long-term performance of FRP materials impose heightened concerns about the overall durability of the structure during service life. These effects include exposure to moisture, saline solutions, chemical solutions, elevated temperature and ultraviolet radiation.

This research investigates the long-term performance of simply supported concrete beams reinforced with GFRP rebars subjected to harsh and changing environmental conditions under sustained load. Actually, studying the long-term behavior of FRP reinforced concrete elements is rather complicated with regard to possible degradation of reinforcement under severe service conditions. Therefore, *previous research work has* been concerned with optimization of the FRP materials and accelerated aging of rebar durability. However, short-term experiments in aggressive environments can only enable quick comparisons of materials, while extrapolation of the results to field conditions and expected life times are not possible in the absence of real-time data [1].

The following section intent is to provide recent knowledge about the degradation mechanisms affecting the mechanical properties of GFRP rebars under exposure to alkaline environment, alternate wet/dry cycles, salt solutions and sustained stress as *these factors are considered in the current research.*

2. ENVIRONMENTAL EFFECTS

Generally, durability tests studying the tensile and bond properties of FRP reinforcement have shown

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that these properties may decrease, remain the same or even increase, depending on the FRP materials and exposure conditions [2]. Recent studies by Homam and Sheikh [3] demonstrated that exposure to a single environmental agent did not result in a significant loss of the mechanical properties and combinations of these agents should be considered in durability tests. Compared to other environmental agents, the alkali attack associated with a high temperature is the most detrimental for GFRP rebar durability [4]. Concrete reinforcement acts in a naturally alkaline medium with an initially high pH value between 12 and 13 depending on the properties of the concrete mix [5]. This environment could damage the glass fibers resulting in loss of strength and stiffness [6]. However, this effect is only operative in moist environment providing the necessary medium for migration of alkali ions. The results of short-term tests showed that the reduction in tensile strength (in the range of 0-70%) and the reduction in stiffness (in the range of 0-20%) varied tremendously with regard to the variation in test specifications and the properties of the tested FRP material.

Katsuki and Umoto [7] proposed a model to simulate the alkali penetration process in GFRP rebars and to predict the degradation in tensile strength and showed that glass fibers were the most vulnerable by the alkali attack compared to other fibers. Their work was later extended by Vijay, et al. [8], who investigated the moisture absorption of GFRP rebars under tap, salt and alkaline water. The amount and rate of diffusion were related to strength and stiffness degradation. It was found that alkaline conditioning produced about twice the moister uptake as compared to tap and salt water conditioning associated with more strength degradation. Recently, the physical and mechanical properties of GFRP rebars were evaluated by Micelle and Nanni [9] by conducting accelerated aging tests in which the rebars were stored in a highly alkaline environment at a temperature of 60 °C in the presence of K^+ and Na^+ ions. In a second exposure regime, the rebars were subjected to a combination of environmental cycles of freeze-thaw, relative humidity, elevated temperature and indirect ultraviolet radiation. Gravimetric measurements, tension tests and short beam tests were performed. The results demonstrated the important role of temperature in increasing the degradation process. Among five different resin types, polyester yielded the highest ratio of weight increase due to absorption of the alkaline solution at high temperature; demonstrating less capacity of protection against alkali attack. Tension tests showed that the sand coated GFRP rebars made using polyester lost about 40% of their strength after 42 days in alkali solution, while this ratio was limited to only 7% in the second exposure regime without significant loss in stiffness in the two cases. A similar behavior was noticed for the horizontal shear strength, reflecting the resin quality and fiber-matrix interface properties, that was severely damaged in the alkaline solution and was not affected by the environmental cycles. Based on these results, it can be concluded that the selection of the resin type is critical for durability performance and that an alkaline medium simulating that of concrete associated with a high temperature can be determinant for durability of GFRP rebars.

The durability of bond between FRP and concrete has been usually conducted in a moist alkaline environment. The environmental agents causing the resin or resin-fiber interface to degrade influence the bond durability of FRP reinforcement because bond relies upon shear transfer and interface transverse forces, which are resin-dependent mechanisms [1]. Clark, et al. [10] conducted pullout durability tests in environments including different alkalinity levels, wetting and drying, chloride and carbonation in moderate temperatures of 20 and 38 °C. The results evaluated over time for stressed and non-stressed pulled rebars showed that the bond strength was insignificantly reduced after two years.

GFRP reinforced beams are usually designed to carry sustained loads producing a stress level of about 20-30 % of the design rupture stress to avoid premature failure due to creep rupture [2]. Nikurunziza, et al. [11] conducted accelerated creep rupture tests on GFRP rebras at an elevated temperature. One group of rebars was stressed at 30% stress level and immerged in salt water, while the rebars in a second group were stressed at 40% stress level and immerged in an alkaline solution. The losses in the tensile strength were found to be 4% and 11% for the first and second groups, respectively, after 60 days. In their early work on the durability of FRP, Tannous and Saadatmanesh [12] evaluated the residual flexural capacity of concrete beams reinforced with GFRP bars and steel stirrups. The beams were stored unloaded for two years in 7 % concentration $NaCl + CaCl_2$ (2:1) solution. Flexural testing of the beams and tension tests of the bare exposed rebars showed that concrete provided good protection by reducing the penetration rate of moisture and salts. Obviously, this conclusion might not be true as the test beams were un-cracked, while concrete beams are usually cracked during their service life. Later, Singhavi and Mirmiran [13] studied the creep and durability performance of environmentally conditioned GFRP reinforced concrete beams. The deformations in four beams were monitored for six months as the beams were loaded in air, water, seawater and de-icing salt solutions. High concentrations of NaCl and $CaCl_2$ were used to simulate the long-term behavior of seawater and deicing salt solution, respectively. The results showed that the accelerated conditioning increased the creep rate of the rebars. On the other hand, the presence of salts did not affect the creep rate of the beams and the moisture absorption of the rebars. Testing the beams till failure after partial creep recovery showed that the post-cracking stiffness of the beams was reduced due to stiffness degradation of reinforcement after environmental conditioning. The reserve ultimate capacity could not be assessed as the beams failed in shear because no transverse web reinforcement was used. Recently, Almusallam [14] conducted creep rupture tests on GFRP rebars in concrete beams. The beams were provided with no stirrups to facilitate extraction of the rebars that were surrounded by a mortar of high alkaline cement. The beams were either unloaded or loaded to produce 20-25 % stress level in the rebars. The beams were conditioned under seawater at 40°C for 120 days. It was found that the non-stressed rebars lost 5% of their tensile strength, while this ratio was as high as 30% in case of stressed rebars; demonstrating the concept of creep rupture.

3. RESEARCH SIGNIGICANCE

This research aimed to investigate the long-term and durability performance of GFRP reinforced beams under the combined action of aggressive environment and sustained load. Identical steel reinforced beams are tested under the same conditions for comparison. The importance of this research is based on current research needs, knowing that the available data addressing the long-term behavior of FRP reinforced concrete beams is scarce. Most durability studies have been carried out on non-loaded beams or bare FRP reinforcing bars. Also, the available few long-term studies on FRP reinforced beams either did not account for the environmental effects or performed on improperly designed specimens. This research provides important data for the designer engineer concerning the influence of sustained load on the deformations of GFRP reinforced beams and the effect of combined sustained load and environment on the durability of materials and structural performance. Also, possible strength and stiffness degradation of GFRP rebars and its impact on the flexural capacity and serviceability in terms of creep rate and cracking are investigated.

4. MATERIALS AND TEST SPECIMENS

A total of six beams were cast and tested. The beams were divided into two series S and F reinforced with steel and GFRP rebars, respectively. The following tests were conducted to determine the long-term and durability parameters of simply supported steel and GFRP reinforced beams:

Test 1: Four-point bending test to determine the initial flexural capacity (Beams S0 & F0).
Test 2: Creep-durability test under uniform sustained load (Beams S & F).
Test 3: Creep-durability test under uniform sustained load and environmental conditions (Beams SE & FE).
Test 4: Four-point bending test to determine the reserve flexural capacity after long-term loading (Beams S, F, SE & FE).

The following sections provide detailed description of the materials used, design of test specimens and testing procedures.

4.1 Materials

Concrete: two concrete mixes were proportioned using ordinary Portland cement, crushed dolomite with a maximum nominal size of 14 mm, graded sand with a fineness modulus of 2.42 and tap water. Beams S0, F0, S and F were cast using concrete mix *I* with a mix ratio of 1: 0.57: 3.33: 2 (cement: water: dolomite: sand). Environmentally conditioned beams SE and FE were cast using concrete mix *II* with the same mix proportions as mix *I*, yet the mixing water contained the following amounts of dissolving salts by weight: 2.4% NaCl, 2.8% Na_2So_4 and 2.4% $MgSo_4$ with a total concentration of 76,000 mg/l. These amounts of added salts were computed to provide total dissolving chloride and sulphate ions of 1% and 4% of cement weight, respectively. The amounts of dissolving ions were determined in the supplied aggregates and consequently the amounts of extra salts to be added to the mixing water were computed. It is worth mentioning that the selected concentration of chloride ions was 10 times higher than that allowed by the Egyptian Code 203/2004 [15] in order to accelerate the corrosion mechanism in beam SE. Three cylinders 150x300 mm and three prisms 100x100x500 mm were cast and tested after 28 days to determine the mechanical properties for each mix including the compressive strength (f'_c), modulus of elasticity (E_c) and modulus of rupture (f_r). Another six cylinders were cast and stored in the same conditions as in tests 2 and 3 and tested in compression after one year. Table (1) shows the mechanical properties of the two mixes at 28 and 365 days.

Table 1 Concrete mechanical properties

Mix	Age *days*	Mechanical Properties (MPa)		
		f'_c	f_r	E_c
I	28	25.0	3.0	22 800
	365	29.8	--	24 200
II	28	26.5	3.3	23 500
	365	32.6	--	25 350

Steel: Deformed high tensile steel bars with a nominal diameter of 12 mm were used as longitudinal reinforcement with a yield stress of 448 MPa. The transverse reinforcement consisted of 6-mm mild steel stirrups with a yield stress of 285 MPa.

GFRP bars: Sand coated 12.5 mm in-house produced GFRP bars were used as longitudinal reinforcement. The manufactured bar had about 60 percent by volume E-glass fibers in a polyester matrix. The bar surface was coated with 0.7-1.2 mm sand particles and finally a thin layer of polyester was applied to the surface to improve the adhesion of sand. The 8 mm GFRP stirrups, shown in Figure (1), were shaped before resin cure at a bend radius of 24 mm. The produced 12.5 mm bars had an average tensile strength of 650 MPa and a modulus of elasticity of 40 GPa, while the average tensile strength of the 8 mm bar was 750 MPa with a modulus of elasticity of 45 MPa. These results were obtained by conducting three bending tests according to the procedure described in reference [16].

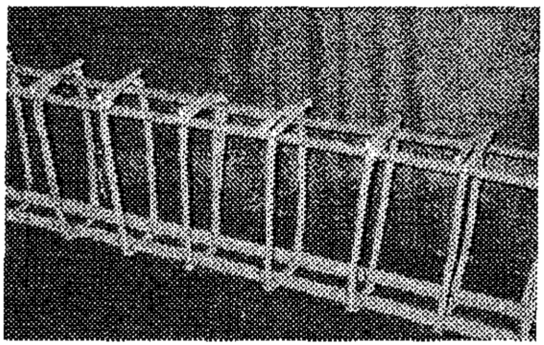

Fig. 1 GFRP reinforcing rebars and stirrups

4.2 Design of test beams

The test specimens included three beams in series S (100x200x2700 mm) reinforced with two 12 mm steel bars at a depth of 178 mm and 6 mm closed steel stirrups at 100 center-to-center spacing along the span. Series F included three beams (100x250x2700 mm) reinforced with two 12.5 mm sand coated GFRP rebars at a depth of 225 mm and 8 mm close GFRP stirrups at 100 mm center-to-center spacing along the span. The dimensions and reinforcement ratios were selected to provide the same ultimate moment of resistance based on the design provisions of the ACI 318-95 code [17] and the ACI 440 1R-03 design guide [1] utilizing the actual material properties and the reduction factors set according to the design provisions. The reduction factors included a computed strength reduction factor of 0.7 to determine the ultimate capacity in F series beams and a specified environmental reduction factor of 0.8 to determine the rupture stress of the GFRP rebar. Table (2) shows the basic design parameters in terms of the reinforcement ratio (ρ), balanced reinforcement ratio (ρ_b), nominal load (P_n), ultimate load (P_u), nominal shear strength component provided by concrete (V_c), nominal shear strength component provided by stirrups (V_s), nominal shear strength (V_n) and the factor of safety against shear failure ($2V_n/P_n$). The loads P_n and P_u and the factor of safety against shear failure are defined in four-bending test. Figure (2) shows the position of the concentrated loads acting on the beams under four-point loading in tests 1 and 4.

Table 2 Design details of the test beams

Beam	S0, S, SE	F0, F, FE
ρ	0.012	0.011
ρ/ρ_b	0.52	1.65
P_n (kN)	32.2	43.4
P_u (kN)	29.0	30.4
V_c (kN)	14.74	4.30
V_s (kN)	28.25	20.65
$2V_n/P_n$	2.67	1.15

Tests 3 and 4 were conducted under sustained loads that were computed based on ultimate strength and serviceability criteria. Serviceability criteria included cracking width, long-term deflection and creep rupture. Series S beams (S & SE) were designed to carry a sustained load of 6.0 kN/m based on long-term deflection criterion, while the corresponding load in series F beams (F & FE) was 7.5 kN/m based on creep rupture criterion. The tensile stress under sustained load in beams F and FE was 20% of the design rupture strength of the GFRP rebar.

4.3 Preparation and testing of beams

All beams were cast in wooden forms and allowed to cure for three days in the forms. The beams were kept moist for 7 days after casting, after which the beams were stored in the laboratory atmosphere for 21 days. All beams were painted over one side using a water-base white paint to facilitate detection of cracks. Tensile and compressive strains were measured using a demountable mechanical strain gage. Punched steel disks were affixed at a gauge length of 200 mm on both sides of the test beam at the level of the tension reinforcement and also 5 mm below the extreme compression concrete fiber at the positions shown in Figure (2). A description of the testing procedures is given in the following:

Tests 1 and 4: these are four-point bending tests conducted to determine the nominal moments of resistance of test beams neglecting the reduction factors considered in the design. The beams were tested over a simple span of 2.44 m and a shear span of 0.91 m. Both ends of the beam were free to rotate

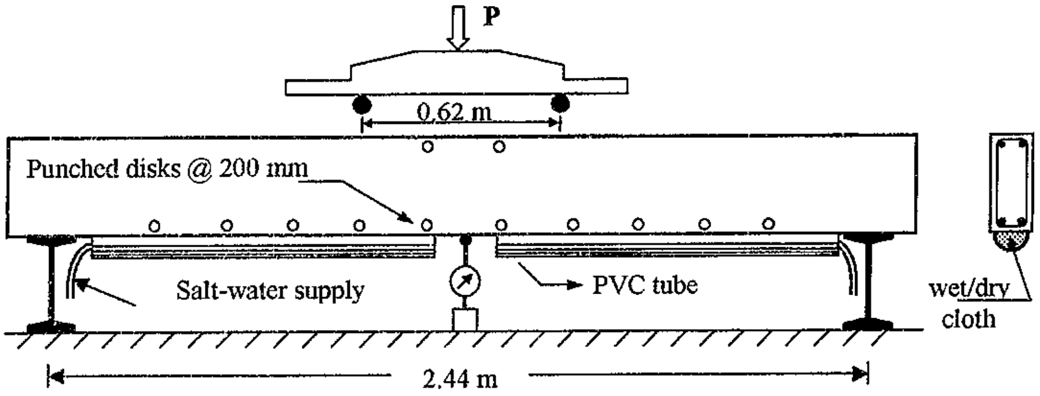

Fig. 2 Test set-up for long-term loading and position of concentrated loads in tests 1 & 4

and translate under load. The load was applied by means of a 100 kN capacity flexural machine. The machine is equipped with a digital control console. The load was applied in displacement increments of 1 mm until failure. Mid-span deflection was recorded at each load step using a dial gage.

Tests 2 and 3: these are creep-durability tests conducted under a uniformly distributed sustained load. Each pair of identical beams (S & SE) and (F & FE) was loaded utilizing cross RC beams distributed along the span. These beams were supported directly on the longitudinal test beams and carried the sustained dead weight provided by 15-cm concrete cubes. The number of cubes was computed to provide the predetermined sustained load. Figure (3) shows front and side views for the test beams under load and shows the rigid steel I-beams supporting the longitudinal test beams. It can be seen that a sufficient gap was left in-between the concrete cubes to maintain a uniform distribution of the dead load as the longitudinal beam deforms with time. Beams S and F were tested in the laboratory atmosphere, while beams SE and FE were further subjected to environmental conditioning of wet/dry cycles using a salt solution. The applied salt solution had the same composition as the mixing water of mix *II* with chloride and sulphate ion concentrations of 14,500 and 38,100 mg/l, respectively. The salt solution was applied by means of a PVC tube that was cut into two halves. The half tube was filled with cloth and attached to the bottom of the beam. The cloth was thoroughly wetted out once a month. Gradually drying, the cloth became completely dry within 8 to 10 days. It was noticed that the wet/dry cycles affected only a zone of 40-60 mm thick at the bottom of the beams. Crystals of salt were seen on the sides of the beams within this zone due to evaporation of the solution. The strains and mid-span deflection were continuously measured over one year followed by creep recovery for ten days upon load release. During this test, both temperature and relative humidity were measured once a week. Statistical results showed that the temperature varied in the range of 26-32 °C with an average of 28 °C, while the relative humidity varied in the range of 68-77 % with an average of 74 %.

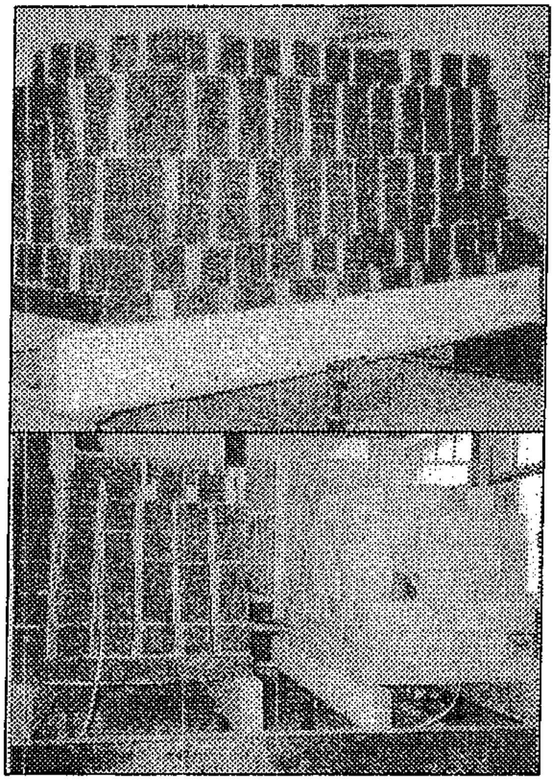

Fig. 3 Test beams under sustained load

5. TEST RESULTS AND DISCUSSIONS

5.1 Tests 1 and 4

These tests aimed to determine the initial loading capacity of test beams at 28 days and the residual capacity after long-term testing and creep recovery at 375 days. Table (3) shows the theoretical and experimental values for the nominal load (P_n). The Table shows that the initial strength was quite well predicted according to the ACI design provisions. Obviously, the load capacity in the over-reinforced FRP reinforced beams is more sensitive to the change in concrete compressive strength compared to the under-reinforced steel reinforced beams. The test results show that beams S and SE failed in flexure and achieved 112 and 107 % of their expected strength at 375 days; indicating good development of strength with time. On the other hand, beams F and FE achieved about 90 percent of the expected capacity. This result can be attributed to the premature failure in beam F that developed a shear-compression failure and consequently did not achieve its full strength, while in case of beam FE the reduction may be attributed to the degradation of bond between concrete and reinforcement as the beam developed its full strength through a flexure failure. Degradation of rebar tensile strength in case of beams FE was not confirmed as the beam was over-reinforced and thus the rebar strength was not exhausted.

Table 3 Theoretical and experimental nominal load P_n

Beam	Theoretical	28-days	375-days
F0	43.4	43.0	--
F	48.0	--	43.4
FE	50.0	--	45.6
S0	32.2	33.2	--
S	33.0	--	37.1
SE	33.3	--	35.7

Figure (4) shows the load-deflection relationship for the tested beams at 375 days-age. The Figure shows that beam S had a higher stiffness compared to beam SE during all the loading stages. Despite the fact that all beams were pre-cracked, beam S developed a three stage load-deflection response characterizing the cracking and yield points, while beam SE developed a two stage response. This led to the conclusion that the bond in beam SE could have been damaged due to the harsh environment. This conclusion was confirmed after testing by removing the concrete cover and examining the steel reinforcement. The examination showed that corrosion spread over about 50 percent of the bar length and the average reduction in the bar diameter was about 5 percent. Figure (5) shows the corroded layer and corrosion stains. Figure (4) shows that the load-deflection response for beams F and F0 was linear elastic up to failure. The load-deflection curves were fairly smooth as the beams were pre-cracked and the cracks initially propagated to about 75 percent of the beam height. Also, it can be seen that beam F had higher stiffness compared to beam FE, which supports the conclusion that the bond resistance was affected by the harsh environment.

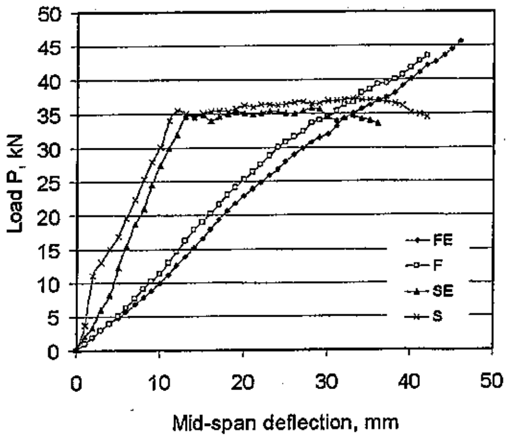

Fig. 4 Load mid-span deflection

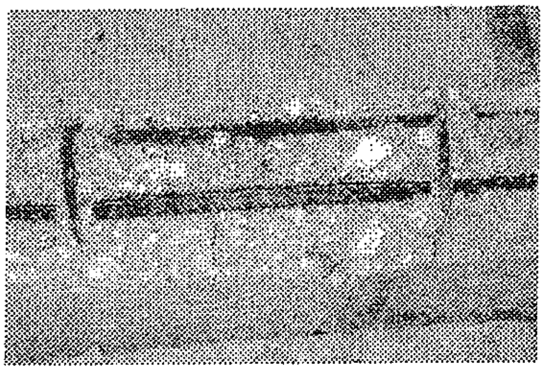

Fig. 5 Corrosion of steel in beam SE

5.1 Tests 2 and 3

These tests were conducted under design service uniform loads that caused initial cracks and deformations. The development of cracks and deformations with time were monitored for a period of one year followed by creep recovery for 10 days. Figures (6-8) show the development of mid-span deflection, tensile strain and compressive strain with time. Figure (6) shows that the deflection development pattern in beams F and FE was very similar. In case of series S beams, the development rate in beam SE increased compared to that of beam S at about 37 weeks. Figure (7) showing the development of tensile strain at mid-span demonstrated a similar trend, yet the strain development rate increased at 25 weeks. Later at 31 weeks, horizontal cracks could be observed at the level of the reinforcement as can be seen in Figure (9), indicating corrosion of the steel reinforcement. Figure (8) shows the development of compressive strain and it can be seen that the development trend is similar in each series. The time-deformation curves in Figures (6-8) show that beams F, FE and SE were still developing deformations by the end of the experiment, while beam S was almost stable after about 31 weeks. Table (4) gives the initial and final

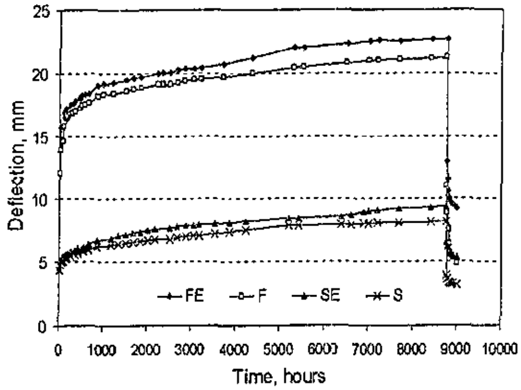

Fig. 6 Development of deflection with time

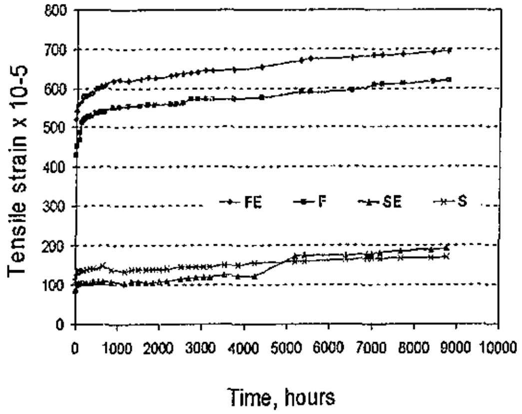

Fig. 7 Development of tensile strain with time

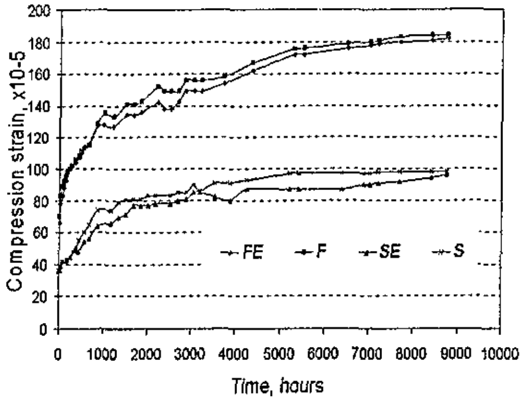

Fig. 8 Development of compressive strain with time

deformations upon load release and the ratio of the final value to the initial one. It is clear that the compressive strain developed the biggest percentage increase in all beams compared to deflection and tensile strain. On the other hand, the percentage increase in the tensile strain in beam SE was higher than that in beam S due to the corrosion induced cracks, so that the limiting ratio of 2.0, representing the design basis for series S beams, was violated.

Table 4: Initial and final deformations of test beams

Beam	Deflection	Strain x 10-5	
		tension	Comp.
F	12.1	430	70
	21.2 (1.75)	618 (1.4)	184 (2.6)
FE	13.8	520	66
	22.6 (1.64)	692 (1.3)	182 (2.8)
S	4.3	110	36
	8.1 (1.89)	169 (1.5)	98 (2.7)
SE	4.6	88	36
	9.4 (2.04)	192 (2.2)	96 (2.7)

Figure (9) shows the initial cracks and development of cracks including newly developed cracks and the extension of the initial ones under sustained load. It was interesting to observe that series F beams did not develop new cracks, while series S beams developed both new cracks and extension of the initial cracks (shown in smaller thickness). This trend can be attributed to the larger width and longer extension of the initial cracks in case of series F beams, reducing the tension stiffening effect and preventing the generation of newer cracks in the block between two initial cracks.

The crack width was monitored using a magnifying microscope and it was found that the limiting 0.04 and 0.07 mm crack width in series S and F, respectively, was not violated as the crack width was limited to 0.01 mm in series S beams and 0.06 mm in series F beams.

6. CONCLUSIONS

Based on the results obtained from the current research, the following main conclusions can be drawn:

1. The long-term performance of GFRP reinforced concrete beams in harsh environment was quite satisfactory compared to steel reinforced beams that showed signs of deterioration due to steel corrosion.
2. Bond deterioration between the GFRP reinforcement and concrete was suspected according to the results of four-point tests.
3. Combining the action of wet/dry cycles and using salt solution containing a high concentration of chloride ions successfully caused the embedded steel rebars to corrode effectively after only 31 weeks.
4. Steel corrosion significantly influenced the structural behavior of the beams in terms of excessive deflections and strains and the development of unfavorable horizontal cracks.

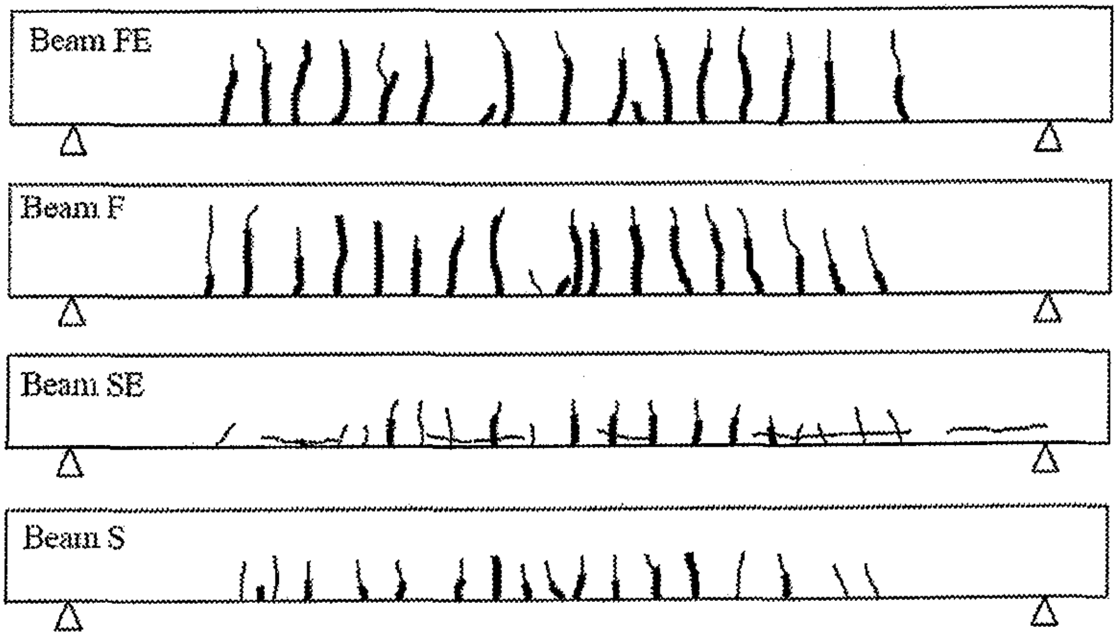

Fig. 9 Initial and final cracks under service load

5. The long-term loading results suggested that the concrete compressive strain could be a limiting design parameter in determining service loads in GFRP reinforced concrete beams. By the end of the experiment, the continuously increasing compressive strain approached a critical value of 0.002 proposing a possible failure due to concrete crushing rather than due to creep rupture.
6. Long-term tension stiffening effect was less pronounced in GFRP reinforced concrete beams and almost no newer cracks developed under sustained load. This trend is attributed to the large width and long extension of the initial cracks.

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