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DURABILITY OF GFRP REBARS IN STRESSED CONCRETE BEAMS AT DIFFERENT ENVIRONMENTS

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ABSTRACT

Long-term behavior of composite materials is still a conventional issue among the engineering community though fiber reinforced polymer (FRP) reinforcements are increasingly used in infrastructure applications. In this paper the effect of sustained loads on concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars is studied. The study comprises casting concrete beams reinforced by GFRP bars and subjected to different environments. All beams were subjected to a certain stress level during their exposure to the environment. An accelerated aging technique is used to simulate the long-term effect. The results of this investigation will be very useful to engineers concerned with the design of structures using composite materials.

Keywords: *Durability, GFRP bars, composites, flexural members, long-term behavior, sustained load.*

الملخص

إن أداء المواد المركبة على المدى الطويل لازال أمراً يخضع للدراسة والنقاش في الأوساط الهندسية رغم أن إستخدامها في البنى الأساسية يشهد تزايداً ملحوظاً . في هذه الورقة تم بحث أثر التحميل المستمر على العوارض الخرسانية المسلحة بقضبان الألياف البوليمرية . وتشتمل على صب العوارض الخرسانية المسلحة بالقضبان البوليمرية وتعريضها لظروف بيئية مختلفة . جميع العوارض تم تعريضها لإجهادات معينة من الحمل المستمر تحت الظروف البيئية المعتبرة في الدراسة ، وقد تم أيضاً إستخدام تقنية تعجيل التفاعل للتنبؤ بالأثر على المدى الطويل . إن نتائج هذه الدراسة ستكون ذات جدوى قيمة للمهندسين المهتمين بتصميم المنشآت الخرسانية بإستخدام المواد المركبة .

1. INTRODUCTION

The reliability of any reinforcement in concrete structures depends mainly on their continued competence to accommodate for the required tensile forces. This means that adequate long-term performance is essential. The suitability and long-term performance of reinforcing steels, used in concrete, are more or less known. But some disadvantages like sensitivity to corrosion do exist specially in environments, such as the one we have in the eastern province of Saudi Arabia.

In recent years interesting developments have emerged in the field of non-metallic elements as a replacement of steel reinforcement in concrete. These alternative reinforcements are based on high strength, high modulus artificial fibers, which are embedded in a polymeric resin. These fibers can be categorized as: glass, aramid, and carbon fibers. The most impressive characteristic of these non-metallic reinforcement fibers is their chemical stability in environments, which are aggressive to steel (e.g. corrosion). The available knowledge and experience about application and long-term behavior of the new materials such as glass fiber reinforced polymer (GFRP) bars, is still restricted. The GFRP bars were used in concrete in the beginning of nineties, mainly in USA and Japan.

The developments were strongly supported by industries operating in the glass composite sector and until recently, worries about durability of glass based bars in a cementitious environment were almost neglected. However, excellent mechanical and corrosion resistant characteristics have promoted the use of FRPs in many structural applications all over the world [Malvar, 1996] and [Nanni, 1993]. Although the short-term mechanical properties of GFRP materials are usually well documented, long-term durability issues still remain.

FRP composites are superior to steel bars. They are economical structural materials for rehabilitating our nation's deteriorating infrastructure or for reinforcing new constructions. However, selection of proper FRP materials to reinforce or repair an aged concrete structure is a complex task. Wide scale usage of FRP products is seriously hindered by lack of experimental and field data and understanding of durability aspects under real-life weathering such as freeze-thaw cycles, alkaline and deicing chemical exposure, and mechanical stress cycles (live loads).

To assure long-term durability of GFRP bars, fundamental understanding is essential in terms of strength, stiffness, and bond degradation. Long-term response of GFRP bars can be obtained by evaluating individual and combined effects of bars under sustained stresses, alkaline and other chemical (salt) reactions, and hydrothermal exposure, and also evaluating concrete beams reinforced with GFRP bars. Accelerated testing and evaluation program are needed to evaluate the expected service performance of individual GFRP bars as well as concrete beams reinforced with these bars. In addition, calibration of the accelerated test results with natural weathering data of in-service structures is needed to establish safe service life of a structure.

The objective of this paper is to investigate the long-term durability of a new generation of GFRP bars under a sustained load in different exposure conditions. This can be achieved and best represented through testing concrete beams reinforced with GFRP bars and subjected to a certain stress level. In order to accelerate the reaction, all beams were completely or partially immersed in different environments (tap-water and sea-water) at elevated temperature. The results of this investigation will provide a certain confidence level in using GFRP bars in concrete structures taking into account the durability issue (i.e. long-term behavior of concrete beams with GFRP reinforcement).

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2. PREVIOUS STUDIES

Glass fibers are the most commonly used fibers in FRP composites. Glass fibers are made from molten glass spun from an electrically heated platinum-rhodium alloy bushings (or furnace) at a speed of 200 mph [Mallick, 1993]. These filaments cool from a temperature of 2192 °F to room temperature within 10^{-5} seconds. Glass fibers have a diameter ranging from 0.000090" to 0.00035". Two hundred and four filaments are grouped together with a lubricant into "strands" during a process called sizing. Strands are combined to form thicker bundles than rovings [CISPI, 1992]. The size is a mixture of lubricants (which prevent abrasion between filaments), antistatic agents (which reduce static friction between the filaments), and a binder (which packs the filaments together into a strand [Mallick, 1993].

Most composites exhibit a long-term static strength that is significantly lower than the short-term strength. This long-term static strength is observed by exposing the material to sustained stress for a long period of time in a certain environmental exposure (i.e. in air, acid, alkaline, sea water at ambient temperature). This failure due to the degradation of the material properties with time is also referred to as creep rupture. The loss of strength can be accelerated in adverse environments, such as, in the presence of water, or strong acidic or alkaline solutions.

Reduction in original properties of GFRP bars may occur under harsh environments and under physical aging, jeopardizing structural safety and effectiveness of composite systems [GangaRao et al., 1995]. The extent of degradation may be accelerated under high pH environment of concrete, sustained stress, and exposure to freeze-thaw conditions. Hence, understanding the durability of GFRP bars as a function of glass fibers and polymeric resin is essential to design GFRP reinforced concrete members and to guarantee the typical infrastructure service life (~75 years), and safety.

The long-term static strength of polystal E-glass tendons at 10,000 hours (about 1 year) has been reported to be 70% of the short-term static strength [Wolff and Miesseler, 1989], [Taerwe, 1993]. Sultan et al. (1995) reported that remaining strengths after 10 to 15 years of 40% for hand laid-up fiber glass, and 50% for filament wound composites. [Slattery, 1994] reported that long-term tests on Glass/Epoxy composites showed failure of about half of the samples tested at a sustained stress of only 50% of ultimate, after about 7 years. [Fujii et al., 1993] tested E-glass composites with relatively brittle polyester matrix. These composites showed significant matrix microcracking when loaded only 40% of their short-term ultimate strength. This microcracking resulted in a significant loss of tensile strength (more than 50% in 720 hours) when the composite was immersed in an acidic solution.

[Sen et al, 1993a, 1993b] tested 12 beams pretensioned with 3/8 inch fiber glass strands. Some of the beams were precracked and exposed to simulated tidal cycles in a 15% sodium chloride solution. Three of the precracked beams failed at a load lower than the cracking

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load, indicating a total loss of the fiber glass starnds after less than 9 months of exposure. One of the uncracked beams failed without the application of any external load (exposure time 18 months).

Tests at Iowa State University used accelerated aging techniques to determine the long-term strength of GFRP composites [Porter et al., 1996a, 1996b]. The accelerated aging procedure involved exposing specimens to an alkaline solution at high temperature (up to 140 ^{o}F) for 2 to 3 months, simulating about 50 years of exposure to real weather. Tensile tests on 3 rebar types indicated remaining strengths of 34%, 52%, and 71% of the measured short-term strengths.

Local studies at King Saud University on the durability of GFRP sheets (Almusallam et al., 2001, Al-[Salloum et al., 2001] and GFRP bars [Alsayed and Alhozaimy, 1998] for unstressed composites have been conducted at different extreme environmental conditions. The studies showed the strength reduction due to environmental exposure.

3. EXPERIMENTAL PROGRAM

3.1 Beam Details

A total of 24 concrete beams of (100 x 100 x 2000 mm) were prepared for this study with 1ϕ10 mm GFRP rebars placed at the tension side (bottom). No stirrups were provided for all beams in which the concrete was chosen such that the concrete will carry all shear forces without having a chance of shear failure for all beams. The beams were designed to be loaded with sustained load which provide 20-25% stress level on the GFRP bars of their ultimate tensile capacities. The GFRP bars were coated with high alkali cement paste (40 x 40 x 700 mm) at the middle to increase the alkalinity content around GFRP bars and to allow easy extraction of bars from beams at the day of testing. The beam cross-section and details are shown in Fig. 1.

3.2 Material Properties

3.2.1 Concrete

The compressive strength of concrete, f'_c, was determined by testing standard concrete cylinders that were taken from the mix patch used for all beams after 120 days. The average value of f'_c was 43 MPa. The high alkali cement paste used for the middle part of all beams (see Fig. 1) has a 0.6 water cement ratio. In order to increase the alkalinity in the paste Na_2O was increased from 0.2% to 1% (about 3.62 kg of NaOH for 350 kg cement). The specified weight of NaOH pellets were dissolved in the mixing water and then cement added gradually. The average compressive strength of (50 x 50 x 50 mm) paste cubes at the day of testing was about 44.2 MPa.

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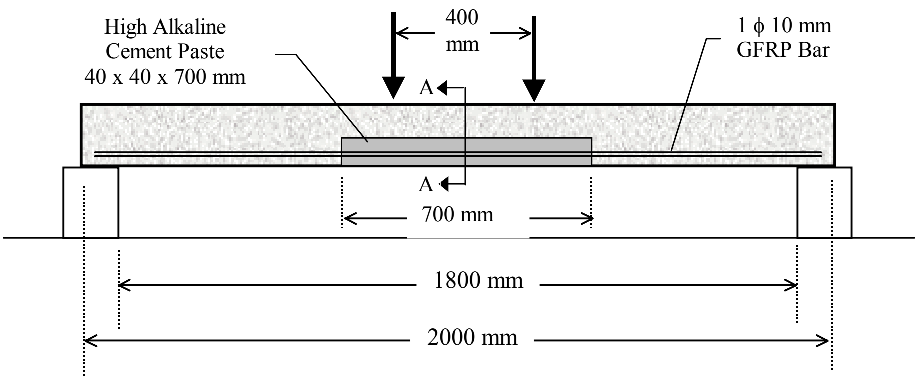
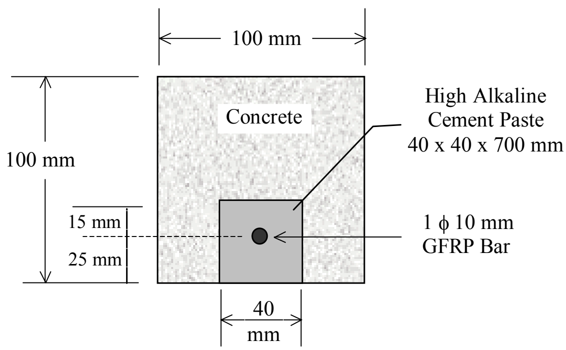
3.2.2 GFRP bars

All beams were reinforced with ϕ10 mm GFRP bars for this study. The type of GFRP bars as described by the manufacturer is E-glass with modified Vinylester polymer with 60% volume fraction of E-glass fiber. The average ultimate tensile strength and modulus of elasticity of 4 samples were determined to be 743 MPa and 39 GPa, respectively. This value of ultimate strength will be considered as the reference value for tensile strength of GFRP bars.



(a) Beam set-up



(b) Beam cross-section (Section A-A)

Fig. 1 The beam specimen details

3.3 Beams and Environmental Groups

After casting and curing all 24 beams, they were subdivided into 3 groups based on their environmental exposure. Each group consisted of 8 beams reinforced with GFRP bars to be exposed to a certain environment. Three tanks were fabricated for the three groups and painted with an enamel paint for protection and fitted with electrical heaters and thermostat to control the temperature of water to about 40 °C. The tanks were designated as T1 (for tap water continuous exposure at 40 °C), T2 (for sea water continuous exposure at 40 °C), and T3 (for wet/dry cycles every 2 weeks in sea water exposure at 40 °C). Each tank contains 8 beams, in which 4 beams were unloaded and the other 4 were loaded with sustained dead loads of about 230 kg on each. This load causes about 22% stress level in the GFRP bars. It is worth mentioning here that the Arabian Gulf is the source of the sea-water used in this study. The details for all beams in all tanks are summarized in Table 1. A sketch that shows the arrangement of the specimens in each tank is shown in Fig. 2.

Table 1: Detail of the specimens in the three tanks.

Tank Designation	Exposure condition	Loading Condition	No. of Beams	Description
T1	Tap water (40 °C)	Unstressed	4 B1, B4 B5, B8	All beams in this group were not loaded to see only the effect of the environment on GFRP bars.
		Stressed	4 B2, B3 B6, B7	All beams in this group were loaded such that the GFRP bars were stressed to about 20-25% of their ultimate tensile strength.
T2	Sea water (40 °C)	Unstressed	4 B1, B4 B5, B8	All beams in this group were not loaded to see only the effect of the environment on GFRP bars.
		Stressed	4 B2, B3 B6, B7	All beams in this group were loaded such that the GFRP bars were stressed to about 20-25% of their ultimate tensile strength.
T3	Sea water wet/dry (every 2 weeks) (40 °C)	Unstressed	4 B1, B4 B5, B8	All beams in this group were not loaded to see only the effect of the environment on GFRP bars.
		Stressed	4 B2, B3 B6, B7	All beams in this group were loaded such that the GFRP bars were stressed to about 20-25% of their ultimate tensile strength.

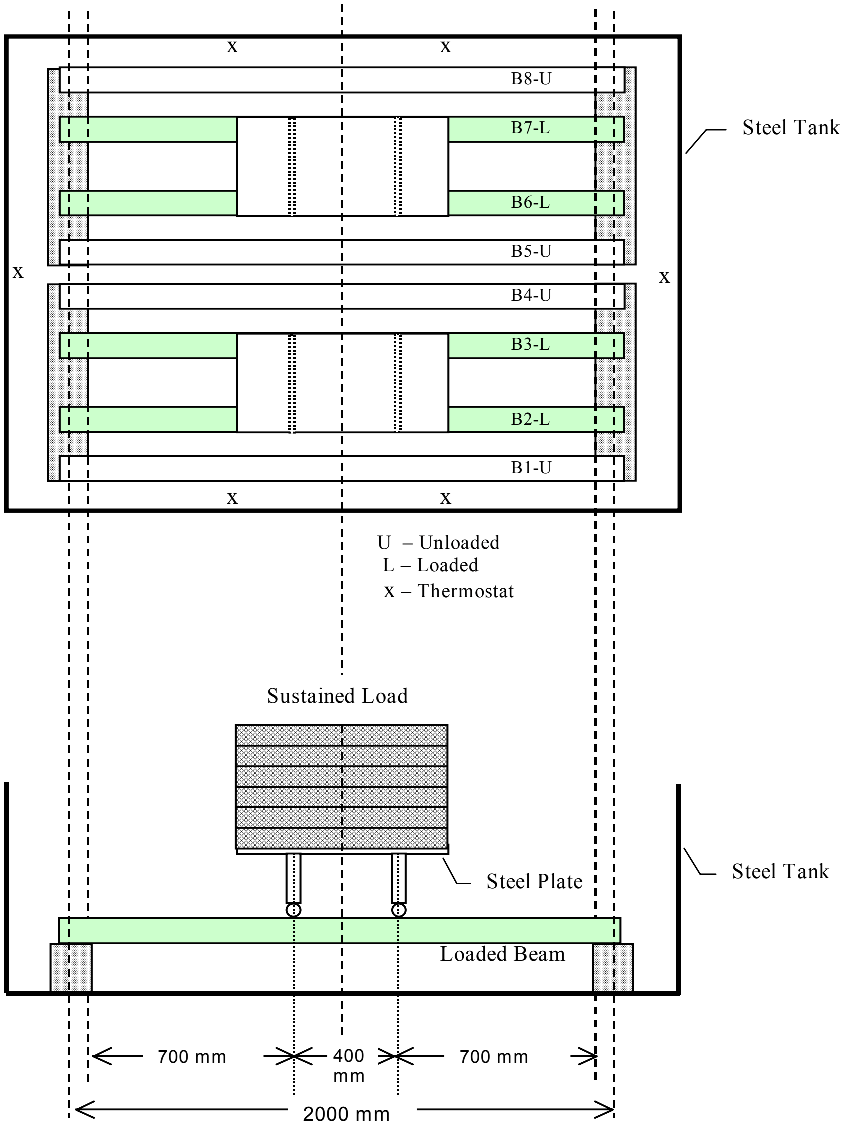


Fig. 2 Arrangement of specimens in each tank.

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3.4 Preparation of Test Specimens

All beams were prepared such that the GFRP bars can be extracted easily from beams with minimal damage to the bars. This was achieved by casting the cement paste (with high alkalinity) around the middle part of the GFRP bars as shown in Fig. 1. Also all bars were connected with 3 strain gages at the middle part of each bar embedded in all beams for the strain measurements at the day of flexural testing. These strain measurements in the GFRP bars were taken in order to study the stress-strain behavior of GFRP bars after environment exposure under sustained loads. Four beams (2 unloaded and 2 loaded) from each tank were scheduled for the first age of testing (4 months). The other four beams in each tank were also scheduled for the second age of testing (8 months)

4. TEST RESULTS AND DISCUSSION

4.1 Tension Tests

After 4 months of exposure in all environments, four beams from each environment (2 unloaded and 2 loaded) were removed from tanks to prepare samples for testing. The GFRP bars were extracted carefully from all beams and two samples of GFRP bars (50- to 70 mm in length) were taken from the middle of each beam to be ready for tension test. Uniaxial tension tests were performed on the stressed and unstressed GFRP bars using 500 kN capacity universal testing machine, with specially modified grips consists of 10 cm split steel pipes used for gripping the bars after sand coating at both ends. Bars were tested as received directly from the manufacturer without simulating any environmental or loading effects. Data obtained from these bars were utilized as a basis (control) for evaluating the performance (reduction in tensile strength) of conditioned and stressed bars. The tensile strength values of all bars after 4 months of exposure along with their averages are shown in Table 2.

It is clear from Table 2 that the maximum reduction in tensile strength for unstressed specimens was about 10% exhibited for wet/dry sea-water exposure. However, the maximum reductions in tensile strength for unstressed specimens, continuously immersed in tap-water and sea-water exposure were about 5% and 2%, respectively, for 4 months of exposure at 40 °C. For specimens with stressed GFRP bars (20% - 25% of their ultimate), the maximum reduction in tensile strength after 4 months of continuous conditioning in sea-water at 40 °C was about 30%, while the reduction for both continuous conditioning in tap-water and wet/dry cycles in sea-water were about 28%. The average tensile strength variation for all GFRP bars tested after 4 months under all exposure conditions is shown in Fig. 3. All values are compared with the control value to quantify the reduction in the tensile strength in the GFRP bars due to sustained load at different environmental exposure conditions.

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Table 2: Tensile Strength of GFRP Bars (Tested after 4 months of exposure).

Exposure Condition	Loading Condition	Bar Designation	Tensile Strength Value (MPa)	Tensile Strength Average (MPa)	Reduction in Tensile Strength (%)
Unconditioned (control)	Unstressed	CB-1	770	743	--
		CB-2	715		
		CB-3	729		
		CB-4	758		
Tap water (40 °C) (T1)	Unstressed	T1B1-1	698	707	4.9
		T1B1-2	715		
		T1B4-1	710		
		T1B4-2	704		
	Stressed (20-25%)	T1B2-1	571	536	27.9
		T1B2-2	523		
		T1B3-1	530		
		T1B3-2	520		
Sea water (40 °C) (T2)	Unstressed	T2B1-1	736	728	2.1
		T2B1-2	721		
		T2B4-1	734		
		T2B4-2	719		
	Stressed (20-25%)	T2B2-1	523	525	29.4
		T2B2-2	571		
		T2B3-1	495		
		T2B3-2	509		
Sea water wet/dry (40 °C) (T3)	Unstressed	T3B1-1	676	667	10.3
		T3B1-2	661		
		T3B4-1	657		
		T3B4-2	672		
	Stressed (20-25%)	T3B2-1	495	537	27.8
		T3B2-2	550		
		T3B3-1	516		
		T3B3-2	585		

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4.2 Flexure Tests

Flexure tests for some conditioned beams were performed before extraction of GFRP bars. For example, the Load-deflection curves for specimens in tank 3 (under wet/dry cycles of sea water exposure and 40°C) are shown in Fig. 4. The unstressed beam (T3B1) and stressed beam (T3B2) along with the unstressed control specimen are shown in the same figure. The ultimate failure loads and the corresponding deflections are shown in Table 3.

The failure load and the corresponding deflection for the control beam were 7.2 kN and 76 mm, respectively. The unstressed beam (T3B1) failed at 6.5 kN (about 10% less load than that of the control beam) and 58 mm deflection (23.7% less than that of the control beam). The stressed beam (T3B2) exhibited behavior with lower ultimate load (about 5.3 kN, i.e 26.6% less than the unstressed control and 18.5% less than the unstressed beam (T3B1) conditioned at the same environment). The corresponding deflection of the stressed beam (T3B2) was 43 mm (43.4% less than that of the control beam and 26.4% less than that of the unstressed beam (T3B1) conditioned at the same environment. This reduction in ultimate capacity of the stressed beam compared to the unstressed beam under the same environment explains more reasonably the effect of sustained load on the overall behavior of beams.

Furthermore, Fig. 4 shows that both unstressed beams (control unconditioned and conditioned one) experienced similar behavior at the beginning of loading (after cracking of the beam) where some indication of slippage of the GFRP bar took place. This behavior disappeared in the stressed beams. This slippage in the GFRP bar could have been taken place in the stressed beams at an earlier stage when the beam was loaded initially. Furthermore, the stressed beam showed lower initial stiffness than the control and T3B1 beams.

The failure pattern for most of tested beams was of compression type, in which concrete failed at compression zone followed by shear failure at the bond line of GFRP bars. Also, it is worth mentioning that no damage was noticed in the extracted samples of GFRP bars. Some photos of failed beams and tested bars are shown in Figs. 5-7.

Table 3: The flexure test results of beams of Tank 3

	ULTIMATE LOAD		DEFLECTION AT ULTIMATE	
Beam Designation	P_u, kN	Change %	Δ_u, mm	Change, %
Control (Unstessed)	7.2	-	76	-
T3B1 (UnStressed)	6.5	-9.7	58	-23.7
T3B2 (stressed)	5.3	-26.4	43	-43.4

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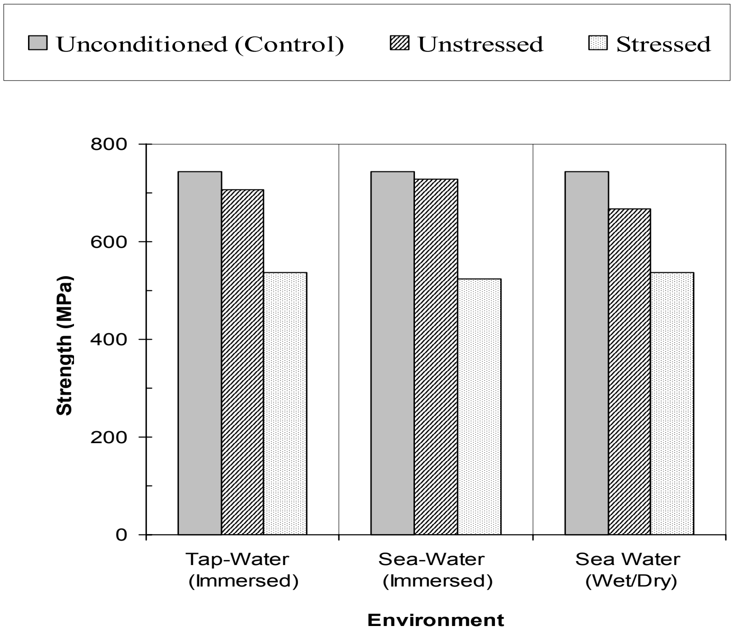

Fig. 3 The average tensile strength variation for all GFRP bars tested after 4 months under all exposure conditions at 40°C.

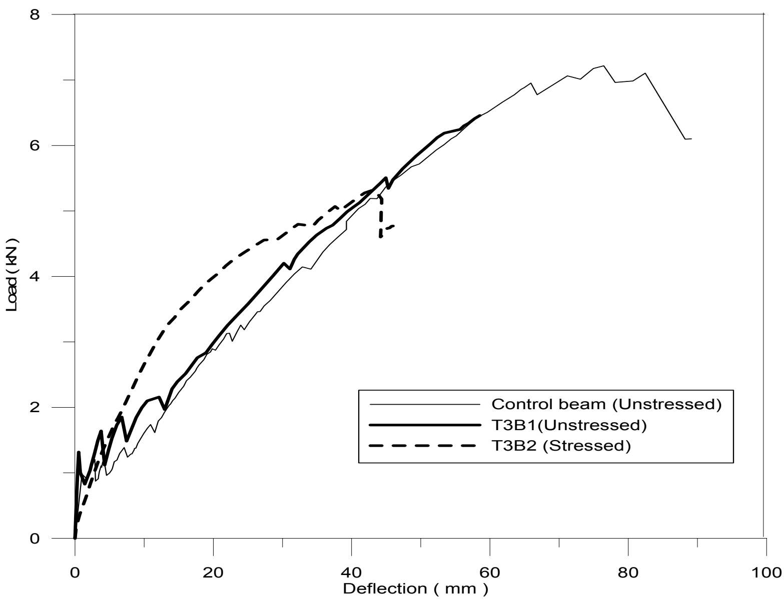

Fig. 4 The load-deflection relationships for beams tested after 4 months of exposure in tank 3 (wet/dry cycles of sea water exposure)

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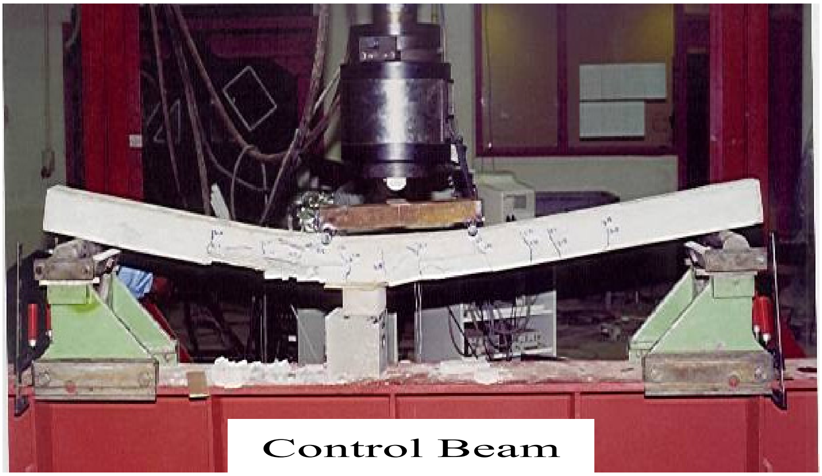

Fig. 5 The control beam after flexure test.

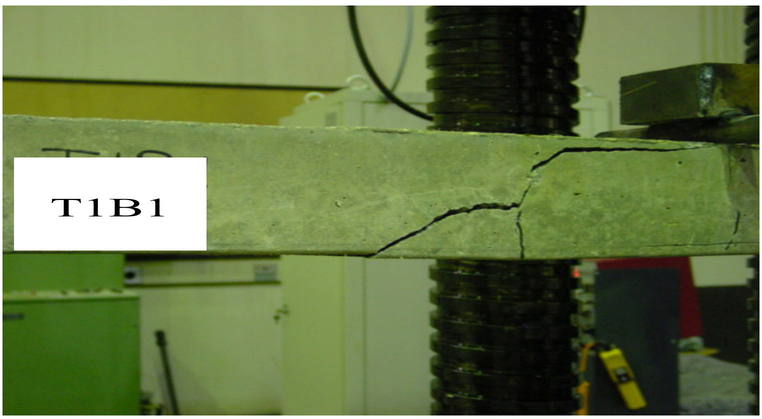

Fig. 6 The T1B1 beam after flexure test

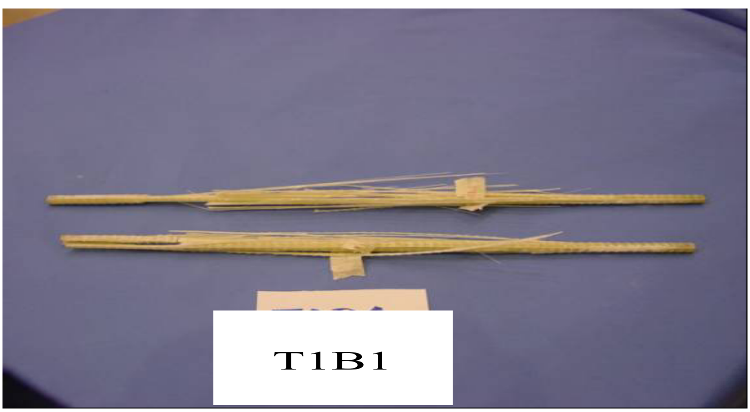

Fig. 7 The bars of T1B1 beam after tension test.

5. CONCLUSIONS

The laboratory test results presented in this study clearly show that there is a significant loss (about 27-29%) in tensile strength of GFRP bars when subjected to sustained stress of about 20-25% of their ultimate for four months in the three environments considered in this study. The loss in tensile strength of the unstressed specimens under the same environments ranges between 2% and 10%. It is clear that the degradation in the GFRP bars is significant when the bars were subjected to sustained stress for a period of time. Similar losses in the flexural strength of these beams were noticed. However, further results will be reported for the counterpart specimens that are currently subjected to the same environments for prolonged period.

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