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Evaluating the Long-Term Performance of Locally Produced GFRP Reinforcing Bars under Sustained Load

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Abstract—In recent years, Fiber Reinforced Plastics (FRP) have been used in different civil engineering applications because of their inherent properties, which include high resistance to loads and environmental conditions. These materials are available in variety of forms including rebars, which have been already manufactured and used abroad in reinforcing of concrete elements in several projects. Unfortunately, these rebars have not been yet widely produced in Egypt. This research is the second phase of a research began by producing FRP rebars locally. In this first phase, short-term tensile properties of locally produced FRP rebars have been investigated. The aim of the current research is to assess the creep behavior of the locally produced FRP rebars under sustained load and comparing this behavior with that of the imported rebars in order to check the adequacy of the locally produced GFRP rebars for structural purposes. For this purpose, creep tests have been conducted on both locally and imported rebars under four levels of sustained service load (nominally 15%, 30%, 45% and 60% of the average ultimate tensile strength) with a creep test duration of 10000 hours (417 days). At the end of the test duration, the samples were tested statically to investigate their residual tensile properties. It has been found out that the creep behavior of the locally produced rebars is comparable to those of the imported ones with the same diameter and approximately the same fiber volume fraction. Creep rupture stress limit was found to be less than 60% of average ultimate tensile strength for the locally produced rebar. Locally produced rebars were found, however, to be satisfying the creep rupture stress limit state stated in ACI 440.1R-15. The Microstructural analysis indicated that there is no degradation in the matrix or the fiber-matrix interface within the GFRP bars after the lengthy duration under sustained load up to 45% of the average ultimate tensile strength.

Index Terms—Glass fiber-reinforced polymers (GFRP), Reinforcing bars, Creep behavior, Serviceability, Sustained service load

1 Introduction

FIBER reinforced polymer (FRP) materials are gaining wider acceptance for use as primary reinforcement in concrete structures. Due to its high strength and non-corrosive nature, FRP provides an alternative to steel reinforcement. The use of FRP as structural reinforcement, in turn, provides the potential advantage of lowered maintenance costs and extended service life for several types of structures, including bridge deck slabs, abutments, walls and other structures exposed to corrosive environments [1],[2]. In the past two decades, a plenty of researches have taken place on fiber reinforced polymer reinforced concrete (FRP-RC) [3],[4],[5]. A better understanding is now available on paramount characteristics such as strength, stiffness, bending, and shear and FRP-concrete bond. Existing guidelines and specifications provide practitioners with the tools they need for the design and construction of FRP-RC structures [6],[7],[8]. Guidelines are periodically updated to reflect advancements in the state-of-the-art and allow for more efficient design where possible.

Under sustained load, FRP bars suffer plastic (permanent) deformation, typically occurring under unfavorable environments over a long time. This phenomenon is what is commonly referred to as “Creep”. Creep typically increases the long term deflection of FRP reinforced concrete elements and may, under certain circumstances, cause catastrophic failure [9]. Despite its higher tensile strength over conventional steel, FRP exhibits less tensile and shear stiffness. As a result of the relatively lower axial stiffness of the FRP bars, FRP reinforced concrete members deform more than their steel reinforced counterparts. Therefore, when FRP bars and tendons are used as reinforcement bars and prestressed tendons, the long-term tensile behavior of these materials must be taken into account in addition to their short-term behavior [10],[11]. Moreover, creep behavior of GFRP is also affected with other adverse environmental conditions yielding a more pronounced effect on GFRP reinforced concrete [12]. Consequently the design of FRP reinforced concrete members is predominantly governed by serviceability requirements.

Based on the findings of researchers such as Yamaguchi et al. [13] and Seki et al. [14] and using the most conservative results available in literature, ACI 440.1R-15 [6] design guideline has assigned GFRP reinforcement the creep rupture stress limit of 20 % of the bar’s tensile strength. Nevertheless, several studies [15] and [16] indicated that if the sustained stress is less than 60 % of the average ultimate tensile strength ($f_{u,ave}$), creep rupture is less likely to occur. They have also suggested that creep rupture stress limits is varying between 45% and 60% ($f_{u,ave}$).

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A recent investigation into available experimental results allowed for an increment of the exploitable capacity under sustained load from 20% to 30% of the guaranteed strength, reduced by an environmental knock-down factor [17]. The new coefficient was adopted in the second edition of AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete [18] and, along with a rationalization of the load demands, allowed for a more efficient design of certain bridge elements [19].

The aim of the current study is to provide essential data on the creep deformation of locally produced GFRP bars under different levels of axial sustained load and in ambient temperature and comparing its creep behavior with that of the imported FRP rebars targeting the evaluation of the adequacy of the locally produced GFRP rebars for structural purposes. The residual tensile properties (modulus of elasticity and tensile strength), after a 10000 hour test-period (417 days), have been observed as well.

The first steps of the current research has been initiated years ago [20], where a pultrusion machine was developed and manufactured, at Properties and Testing of Materials Laboratory, Faculty of Engineering, Ain Shams University, to be used in producing pultruded FRP rebars. Indeed, GFRP reinforcing bars with diameters 10, 13, and 16 mm and with a fiber volume fraction of 60 % have been produced.

It is important to consider that the rate of creep-strain increase tapers down greatly with time when extrapolating the obtained measurements over the service life of a concrete structure (50 years). The 10000-hour period has gained consensus as the period that captures most of the resulting creep strain [9], [12], [13], [21], and [22].

2 Experimental Program

2.1 Materials and Sample Preparation

Both locally manufactured and the imported FRP bars are tested in creep in this study. The locally produced bars (L-Bars) is made of medium-strength E-glass fibers (60 % fiber by volume) impregnated in polyester resin. The bar’s circular cross section has a 10 mm diameter. The imported type (I-Bars) is 9.5 mm in diameter and made of E-glass fibers that constitute 74.2 % of the bar’s volume, as supplied by the manufacturer [23].

Prior to creep test, tensile properties of the tested GFRP rebars are to be determined to be used later in creep test. Therefore, tension test was carried out on the GFRP rebars of both types according to ASTM D7205 / D7205M [24]. Tension test was carried out on three specimens of FRP rebars from each type. GFRP rebars were first prepared to be able to perform tension test. This preparation begins by cutting the rebars into an appropriate length (1000 mm) guided by the recommendations of D7205 / D7205M [24]. Each one of the two ends of the bar sample was fitted into a 300 mm-long steel tube (grip) using an epoxy grout, as shown in Figure (1). After attaching the specimen to the tension test frame illustrated in Figure (2), which was specially design to carry out the tension test on FRP rebars [20] ,a linear variable differential transducer (LVDT) was mounted to a side of the bar at the center of the testing length as shown in Figure (2). The LVDT had a gage length of 200 mm.

The main mechanical properties of the prepared rebars; average ultimate tensile strength $f_{u,ave}$, modulus of elasticity E_f, and average ultimate tensile strain $\varepsilon_{u,ave}$; have been determined according to ASTM D7205 / D7205M [24] prior to creep testing. Tension test results were summarized in Table (1).

Figure 1: Preparation of GFRP bars specimens

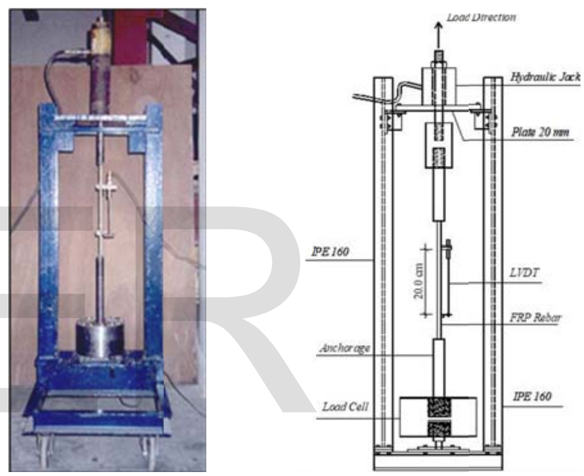


Figure 2: Tension Test Setup

TABLE 1
Mechanical properties of GFRP Reinforcing Bars

	Nomenclature	I-Bars	L-Bars
Ultimate tensile stress (MPa)	$f_{u,ave}$	854 ± 34	760 ± 38
Guaranteed tensile stress (MPa)	f^*_{fu} ($f^*_{fu} = f_{u,ave} - 3\sigma$)	752	646
Design tensile stress[a] (MPa) (ACI 440.1R-15)	$f_{fu} = C_E \times f^*_{fu}$; $C_E = 0.8$	602	516
Modulus of elasticity[b] (GPa)	$E_f = E_{f,ave}$	46.9 ± 1.2	40.8 ± 1.4
Ultimate strain (με)	$\varepsilon_{u,ave}$	18209 ± 767	18627 ± 835
Guaranteed strain (με)	ε^*_{fu} ($\varepsilon^*_{fu} = \varepsilon_{u,ave} - 3\sigma$)	15908	16122
Design tensile strain (με) (ACI 440.1R-15)	$\varepsilon_{fu} = C_E \times \varepsilon^*_{fu}$	12726	12898

[a] The reduction factor ($C_E = 0.8$) is associated with non-exposure to earth and weather.
[b] The design or guaranteed modulus of elasticity E_f equates the mean modulus of the sample $E_{f,ave}$ as per the ACI 440.1R-15 guide [6].

2.2 Study Parameters

The two parameters of interest are the bar-type and the axial sustained load level. For each bar-type, four levels of sustained tensile load (15 %, 30 %, 45 %, 60 % $f_{u,ave}$) were applied, giving a range of initial strain $\varepsilon_{frp,0}$ ranging from around 2000 to 14000 με. One specimen is assigned to each sustained load level per bar-type, i.e., four specimens from each bar type were tested in creep. It has been tried to keep the surrounding environment constant whilst conducting the long-term creep (23 ± 3 °C and 50 ± 10 % relative humidity). The purpose of testing the material at load levels far beyond the allowable is to explore the true capacity of such bars where the available codes and guidelines may be conservative when it comes to GFRP reinforced concrete elements not exposed to earth and weather.

2.3 Instrumentation and Installation of Samples

Following the guidelines of ASTM D7337 / D7337M [25] and ACI 440.3R-12 [26], Creep testing frames have been manufactured at Properties and Testing of Materials Laboratory, Faculty of Engineering, Ain Shams University. Schematic drawing and a photo of the loading frame are shown in Figures 3 and 4, respectively. The schematic of the loading frame illustrates the comprising frame elements and location of the sample within. The aim of such frames is to have a constant tensile load sustained along the bar's length for extended time durations. The load should be maintained perfectly axial as assuring that no eccentricity or bending occurs to the bar is of vital importance. The associated load magnifying system (the two lever arms and the sustained weight-pan) multiplies the kept-on-pan weight to reach a specified percentage of the sample's ultimate tensile capacity $f_{u,ave}$.

As mentioned before, specimens have been prepared by fitting both ends of the bar specimen into two steel pipes using the suitable epoxy grout. In order to fix the specimen in the frame, the steel pipe-grips on both ends were threaded on the outside, to screw/fit onto spherical nuts that keep the sample intact with the frame.

Two 10-mm strain gauges (120 ohm resistance and a gauge factor of 2.10) were attached –on opposite sides- at the middle of the free portion of each specimen. For gauge installation, adhesive was used and gauges were properly aligned in the longitudinal direction of the bar. Each gauge was connected to a portable strain indicator when strain measurements are to be taken. After fitting the specimen in the loading frame, load (calculated earlier from the calibration process) was then applied through some standard weights as illustrated in Figure (4).

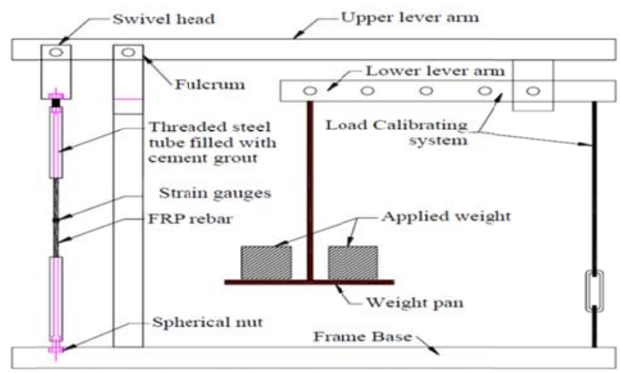


Figure 3: Schematic of bar sustained load frame (magnifying frame)

Figure 4: Creep loading frame

The reinforcing bar elongation measurements were taken as soon as the GFRP bars are installed under the prescribed load, then at following times for the extended test duration (10000 hours at least).

The frequency at which elongation-measurement is recorded decreases with time. For the tests in the current research, readings were taken every six hours for the first two days; every day for the first week; biweekly when the rate of change of creep strain significantly decreases. Each measurement, indicated on the graphs (See Figure 5), is actually an average of the two back-to-back gauges installed onto the bar-sample.

After the completion of the 10000 hour duration, all specimens were uninstalled from the test frames and then tested in tension. Residual tensile properties, indicated as percentage of the average ultimate tensile strength

(% $f_{u,ave}$) and as percentage of the average Young's modulus (% E_f), were determined.

3 Results and Discussion

3.1 Creep Tensile Strain

For any GFRP bar, the creep characteristics are known by monitoring the change in axial strain with time under constant applied stress. The creep behavior of the tested GFRP bars is displayed in Figure 5 as well as Table 2 to Table 4. It was observed that for both bar-types, there was no sign of creep failure for sustained load levels up to to 45 % $f_{u,ave}$. Unlike I-Bars, Creep rupture took place at 60 % $f_{u,ave}$ after 14.6 hours for L-Bars. It is worth noting that I-Bars bars have a higher fiber volume fraction that allowed its sample to sustain a load level of 60 % $f_{u,ave}$ for 10000 hours without creep rupture.

The upper-bound creep-strain percentages for I-Bars as a maximum values after 10000 hours are 9.1, 0.50, 4.1, and 2.8 % for sets 15 %, 30 %, 45 %, and 60 % $f_{u,ave}$, respectively. The corresponding values for L-Bars are 2.5, 5.5 and 9.4 % for sets 15 %, 30 % and 45 % $f_{u,ave}$, respectively (See Table 2 and 3). Unexpectedly, no consistent relationship is evident between the magnitude of accumulated creep strain and sustained load level in the case of I-Bars.

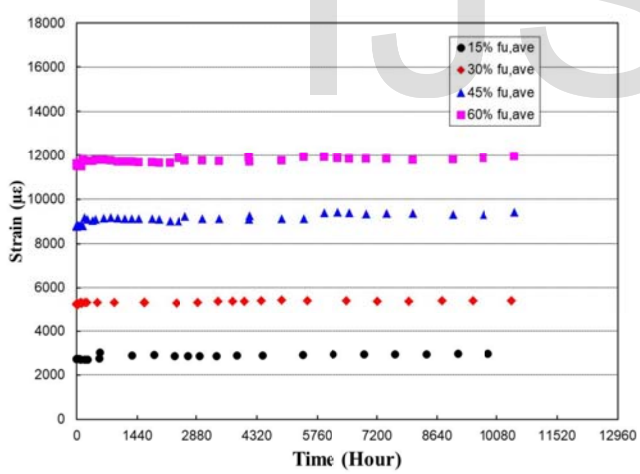


Figure 5a: Strain evolution with time of I-Bars bars

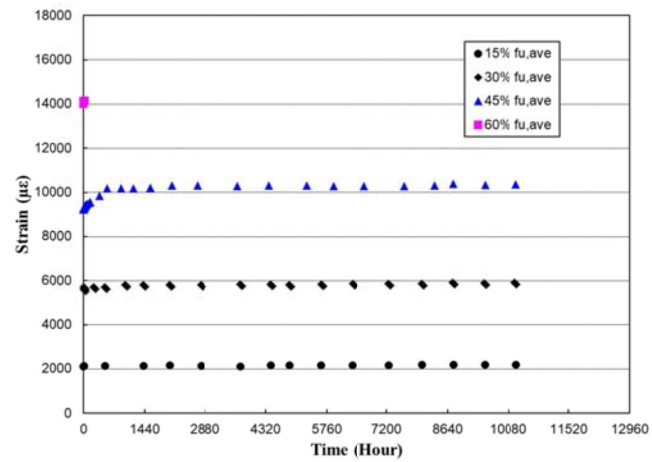


Figure 5b: Strain evolution with time of L-Bars bars

According to ASTM D7337 / D7337M [25], Creep coefficients can be determined by linearizing the creep-strain curve into strain versus log time. When plotted in such a manner, the curve becomes a linear relationship. The equation for the total strain of the commercial bars can be written as:

$$\varepsilon_{frp}(t) = \beta \cdot log(t) + \varepsilon_{frp,0} \qquad \text{Eq. (1)}$$

where $\varepsilon_{frp}(t)$ is the total strain in the material after a time period t (10000 hours for this study), $\varepsilon_{frp,0}$ is the initial (elastic) strain value and β is the creep rate parameter that is equal to $d\varepsilon(t)/dt$. Using linear regression for the obtained data, the creep coefficients of I-Bars samples were determined as 28.7, 44.8, 116.0 and 149.7 for 15 %, 30 %, 45 %, and 60 % $f_{u,ave}$, respectively. Similarly, the creep coefficients for L-Bars samples were 9.7, 68.2, and 273.2 for 15 %, 30 %, 45 % $f_{u,ave}$, respectively where the creep coefficient at 60% $f_{u,ave}$ could not have been determined due to the creep rupture occurrence. It is evident that the coefficient β increases significantly with the increase of applied stress.

Creep tensile strain results indicated clearly that the locally produced rebars possess similar creep behavior to that of the imported ones, excluding the occurrence of creep rupture at stress 60% of average tensile strength in case of L-Bars. The occurrence of creep rupture of L-Bars under sustain load level lower than the case of I-Bars could be ascribed to the lower fiber volume fraction of L-Bars in addition to the expected difference in either the quality of the constituent materials or the manufacturing process itself leading finally to the noticed slight superior creep behavior of the I-Bars. It is worth mentioning, however, that L-Bars satisfy clearly the creep rupture stress limits of FRP reinforcement for GFRP that is stated in ACI 440.1R-15 [6] which is 20 % $f_{u,ave}$.

TABLE 2
I-BARS CREEP-TEST RESULTS (15 %, 30 %, 45 % AND 60 % $f_{u,ave}$)

Nominal Applied Load	$\varepsilon_{frp,0}$	$\varepsilon_{frp,0}/\varepsilon_{u,ave}$ ratio (%)	$\varepsilon_{frp,0}/\varepsilon^*_{fu}$ ratio (%)	Creep Strain (Strain Increase) (με) after			Creep Strain/Initial Strain ratio (% of actual initial strain) after		
				1000 hrs	3000 hrs	10000 hrs	1000 hrs	3000 hrs	10000 hrs
15%$f_{u,ave}$	2631	14.4	16.5	155	145	239	5.9	5.5	9.1
30%$f_{u,ave}$	5674	31.1	35.7	74	39	29	1.3	0.7	0.5
45%$f_{u,ave}$	8195	45.0	51.5	192	179	339	2.3	2.2	4.1
60%$f_{u,ave}$	10416	57.2	65.4	-101	179	292	-0.9	1.7	2.8

TABLE 3
L-BARS CREEP-TEST RESULTS (15 %, 30 %, AND 45 % $f_{u,ave}$)

Nominal Applied Load	$\varepsilon_{frp,0}$	$\varepsilon_{frp,0}/\varepsilon_{u,ave}$ ratio (%)	$\varepsilon_{frp,0}/\varepsilon^*_{fu}$ ratio (%)	Creep Strain (Strain Increase) (με) after			Creep Strain/Initial Strain ratio (% of actual initial strain) after		
				1000 hrs	3000 hrs	10000 hrs	1000 hrs	3000 hrs	10000 hrs
15%$f_{u,ave}$	2105	11.3	13.1	35	34	53	1.7	1.5	2.5
30%$f_{u,ave}$	5600	30.0	34.7	206	230	308	3.7	4.1	5.5
45%$f_{u,ave}$	8977	48.2	55.7	633	757	843	7.1	8.4	9.4

TABLE 4
L-BARS CREEP-TEST RESULTS (60 % $f_{u,ave}$)

Nominal Applied Load	$\varepsilon_{frp,0}$	$\varepsilon_{frp,0}/\varepsilon_{u,ave}$ ratio (%)	$\varepsilon_{frp,0}/\varepsilon^*_{fu}$ ratio (%)	Creep-rupture Time (hour)	Creep Strain Increase at Rupture Time (με)[a]	Creep Strain/Initial Strain at Rupture Time (%)
60%$f_{u,ave}$	14030	75.3	87.0	14.6	332	2.4

[a] Creep strain readings were taken manually; the measurements taken are expected to be less than the actual value at rupture time.

3.2 Residual Tensile Properties (Strength and Young's Modulus)

After the elapse of the test duration (10000 hours), all bars were dismantled from their comprising frames and tensile tests were conducted to obtain residual mechanical properties. For both I-Bars and L-Bars specimens, the rupture mode was burring of the fibers, as shown in Figure (6). The average residual strength was barely affected by creep tests (Figure 7). The maximum percentage loss in strength for I-Bars bars was about 4 % for 60 % $f_{u,ave}$. The corresponding value for L-Bars was almost 5 % for 45 % $f_{u,ave}$ (Figure 7). As for the modulus of elasticity, the residual values showed barely any change from the original values. The average residual modulus was found to be 46.2 GPa 41.0 GPa for I-Bars and L-Bars, respectively.

Figure 6: Typical mode of failure of tested rebars

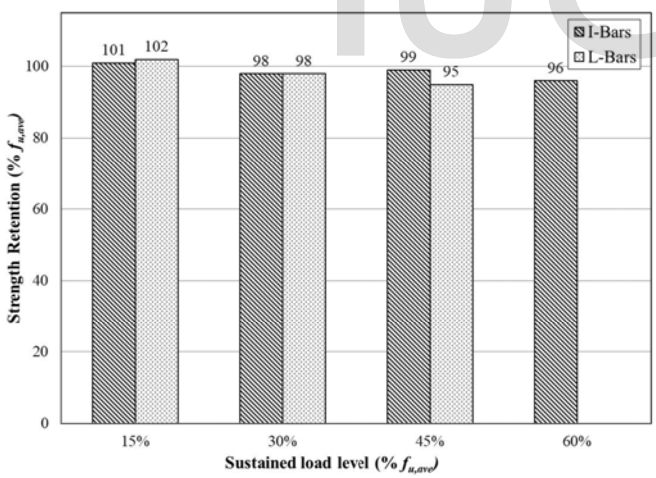


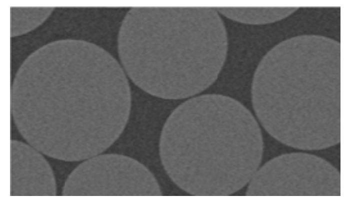
Figure 7: Residual tensile strength for I-Bars bars and L-Bars bars

3.3 Microstructural Analysis

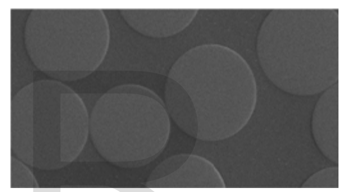
The formation of microcracks in the resin and the debonding at the interface of fibers/matrix are the most common phenomena occurring in a GFRP material under sustained load and/or adverse environment [15], [21], and [12]. In this respect, Scan Electron Microscopy - SEM - analysis took place using selected samples of the tested bars after the 10000 hour test duration to have a better understanding of the causes behind strength loss, if any.

Micrographs, in Figure 8, show magnified cross-section images of I-Bars and L-Bars subjected to 45 % $f_{u,ave}$ and 60 % $f_{u,ave}$ after creep test duration. Results showed that both bar types had no signs of debonding between fibers and resin and no induced microcracks under the sustained load level (45 % $f_{u,ave}$) for L-Bars and under sustained load level (60 % $f_{u,ave}$) for I-Bars. For L-Bars, subjected to 60 % $f_{u,ave}$, thin voids appeared around the fibers (Figure 8c).

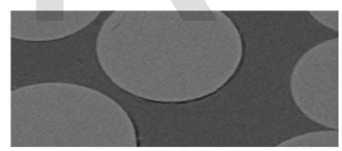
This noticed debonding initiation may reflect, as mentioned before, the difference in quality control on both levels the constituents and the manufacturing process. This debonding as well could justify the rupture of L-Bars that took place after 13.8 hours.



(a)



(b)



(c)

Figure 8: Magnified samples' cross section after exhibiting 10000 hours of loading: (a) I-Bars at 60 % $f_{u.ave}$; (b) L-Bars at 45 %; (c) L-Bars at 60 % $f_{u.ave}$

4 Summary and Conclusion

Creep behavior tests were conducted on both locally produced and imported GFRP reinforcing bars over a period of 10000 hours (417 days at different levels of axial sustained load, nominally (15 %, 30 % 45 % and 60 % of the average ultimate tensile strength $f_{u,ave}$). The following conclusions can be drawn from the current research study:

- Unlike I-Bars, creep rupture took place in L-Bars specimen at 60 % $f_{u,ave}$ whereas no creep rupture was noticed in I-Bars specimens under all sustained load levels, which in turn reflects a slight higher quality of imported bars which is expected. However, creep test results showed clearly that the locally manufactured

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GFRP bars rupture in creep at stress level lies clearly beyond the stress limits specified by ACI 440.1R-15.

- No change was detected in residual tensile strength and modulus of elasticity for all samples that survived the 10000 hour duration and all reinforcing bars have almost retained their initial full strength.
- Microstructural analysis illustrated that no microcracks were found in reinforcing bars of both types up to 45 % $f_{u,ave}$. Under sustained load level of 60 % $f_{u,ave}$, debonding has initiated in L-Bars, whilst, no cracks or deboning was noticed in case of I-Bars. Microstructure analysis emphasized, as mentioned before, the better quality of I-Bars compared with L-Bars.
- Based on the investigations carried out in the current research, it has been emphasized that the creep stress limits imposed by ACI 440.1R-15 on GFRP reinforcement underestimate the stresses GFRP bars can actually sustain.
- Creep test results of the current study in addition to the results of first phase of this research carried out in 2005; refer to the adequacy of the locally produced GFRP reinforcing bars to be used as reinforcement for concrete structures.
- As a recommendation for further research, it is recommended to perform creep test under severe environmental conditions, such as alkalinity and high temperature, for test durations not less than 10000 hours to be able to propose new creep rupture stress limits which could be higher than those specified in ACI 440.1R-15.

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