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СВОЙСТВА ИЗГОТОВЛЕННЫХ В МЕСТНОМ ПРОИЗВОДСТВЕ ПОЛИМЕРНЫХ СТЕРЖНЕЙ, АРМИРОВАННЫХ ГИБРИДНЫМ ВОЛОКНОМ

АННОТАЦИЯ

Полимеры, армированные стеклянным волокном, имеют много преимуществ по сравнению с арматурной сталью, таких как высокая прочность по отношению к удельному весу, высокое сопротивление коррозии, высокое сопротивление усталостным нагрузкам. Один из главных недостатков стеклопластиковой арматуры – податливость. Линейное поведение стеклопластиковых стержней до разрыва делает их применение несравнимым с обычными стальными стержнями. Эксперимент по изготовлению пластиковой арматуры, используя метод пултрузии, позволил получить стержни, включающие стеклянное волокно с углеродным и арамидным в различных соотношениях. Результаты испытаний на растяжение показали, что произведенные в местном масштабе волокнисто-армированные стержни имеют своего рода полуподатливое поведение, подобное арматурной стали.

КЛЮЧЕВЫЕ СЛОВА: Полу-податливость, полимерные стержни, армированные гибридным волокном, пултрузия.

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PROPERTIES OF LOCALLY MANUFACTURED HYBRID FIBER REINFORCED POLYMERS (HFRP) REBARS

ABSTRACT

Glass fiber reinforced polymers rebars (GFRP) have many advantages compared to traditional reinforcing steel such as higher strength to weight ratio, higher resistance to corrosion as well as higher resistance to fatigue loads. One of the main disadvantages of GFRP bars is its lack of ductility. The linearly behavior of the GFRP bars up to failure makes their application incomparable with conventional steel bars. One solution to provide ductility for FRP is a hybrid FRP reinforced bars. A pilot trial to manufacture locally HFRP rebars using the Pultrusion method by the produced rebars consisted of Glass fiber combined with both Carbon and Aramid fiber with three different ratios for each. Tension test results showed that the locally produced hybrid FRP rebars had a kind of semi-ductile behavior similar to some extent to that of conventional reinforcing steel.

KEYWORDS: Semi-ductility, HFRP, pultrusion.

Introduction and background

Fiber-reinforced polymers (FRP) are increasingly attracting the attention of civil engineers worldwide because of such favorable performance characteristics as high-stiffness, high-strength to weight ratio, high resistance to corrosion and magnetic neutrality. Fiber reinforced polymers offer unique advantages for solving many civil engineering problems in areas where conventional materials fail to provide satisfactory performance. Unlike steel, FRP are unaffected by electrochemical deterioration and can resist the corrosive effects of acids, alkalis, salts, and similar aggressive

Fig. 1. Carbon fiber roving

Fig. 2. aramid fiber roving

Fig. 3. glass fiber roving

materials. Due to their superior characteristics such as high tensile strength, corrosion-resistance, FRP gained wide acceptance as an alternative material for steel in applications where steel is subjected to high risk of corrosion. Several products of FRP are commercially available worldwide for their use in different civil engineering applications. Among these products, FRP rebars were emerged as an alternative solution for reinforcing concrete elements subjected to corrosive environments. A variety of fiber-reinforced polymers (FRP), e.g. Glass, Aramid and Carbon, are now available in form of bars. A marked disadvantage of present day FRP reinforcement, as compared to steel, is its lack of ductility. The linearly elastic behavior of available FRP systems up to failure makes their application reinforce concrete structure incomparable with conventional steel. The commercially available FRP rebars are produced by Pultrusion process utilizing continuous monotypic fiber (usually Glass, Carbon, or Aramid) embedded in a resin matrix. It is a continuous process that combines pulling and extrusion for manufacturing composite sections that have the same cross section and shape. In Egypt the FRP rebars have not been commercially produced yet. One of the objectives of this study was the possibility of locally producing hybrid FRP rebars using the Pultrusion method with a random distribution of the different fibers types in the resin matrix. The study also includes the estimation of the physical and mechanical properties of the manufactured hybrid rebars (HFRP) taking into consideration the effect of the different variables considered in the study.

Research program

In order to achieve the research objectives in this paper, the Pultrusion method was used to manufacture locally HFRP rebars using three different types of fibers, glass, carbon, and aramid. Glass, Carbon and aramid fibers were wed with total fiber volume fraction of 61 %. Three replacement ratios by volume were used to replace the glass fibers by carbon and aramid fibers. These ratios were V_C/V_G 5/56, 10,6/50,4 and 19/42,6 for carbon and V_A/V_G 5/55, 9/52,6 and 17/44,5 for aramid. Twenty one bars, circular in cross-section with 8,5 mm diameter, were manufactured. The research program includes testing specimens taken from the manufactured bars for the estimation of the unit weight, fiber volume fraction, and the tensile strength of the HFRP bars. Each test was repeated for at least three times and the average results were considered. Manufacturing process and test results are presented in the following sections.

Materials

The FRP materials used included carbon, glass and aramid fibers and polyester as a resin. All materials used are available in the local market. The used fibers are available in the local market in the form of roving only, Figs. 1, 2, and 3. The properties of carbon, glass, and aramid fibers are given in Table 1. As presented in Table 1, the carbon fibers have relatively the highest tensile strength and modulus of elasticity with low ultimate strain, while glass fibers showed the lowest tensile strength and modulus of elasticity with relatively high ultimate strain.

Table 1

Properties of the used fibers

Property / Type	Tensile strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Strain (%)
E-Glass	2400	70	3.4
Kevlar 49	3000	126	2.38
Carbon	3400	225	1.51

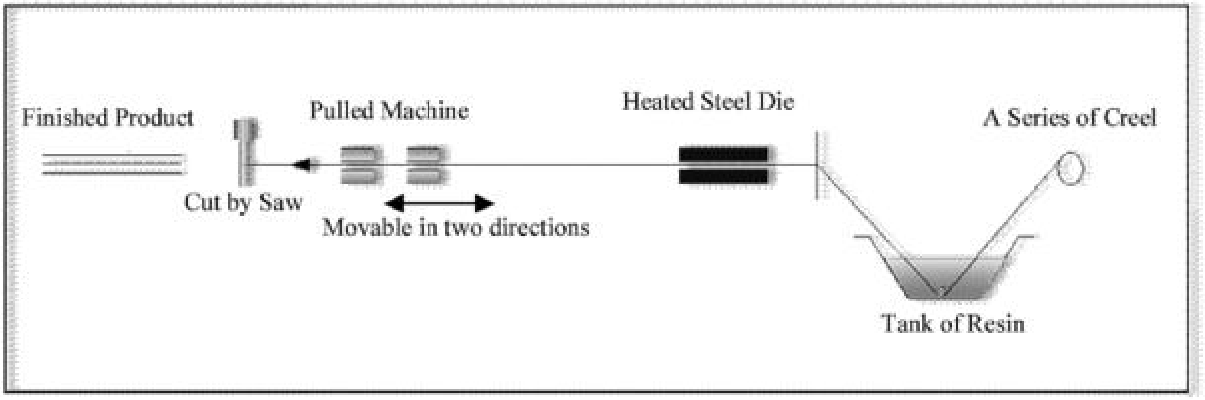

Fig. 4. A Schematic diagram showing the process of pultrusion of FRP-bars

Table 1 shows also that, the aramid fibers mechanical properties fall between those of glass and carbon fibers. The properties of the used polyester resin as provided by the supplier are; tensile strength 40-60 MPa, modulus of elasticity 3,5 GPa and ultimate elongation 5-6 %.

Manufacturing process

All the bars were manufactured using the pultrusion method. A random dispersion of the two fiber types was adopted. The pultruded product is manufactured in 10th of Ramadan Industrial City, 50 km away from Cairo. Figure 4 shows a schematic representation of the pultrusion process. In the pultrusion method the fibers yarns are pulled from a series of creels. Yarns are emarginated with resin (the resin was mixed with peroxide with the ratio of 1000:1) by weight which was enough for the pultrosion of the bars. This composite material is then passed through a heated steel die. Heat initiates an exothermic reaction thus curing the resin matrix. Then, the bar is continuously pulled at constant rate and exits the mould as a hot constant cross sectional bars. The bars then are cooled down in the ambient air. Finally, the produced bars come out from the puller mechanism and are cut to the desired length by an automatic cutoff saw. As shown in Fig. 5.

The used number of fiber yarns controls the fiber volume fraction of the produced bars. Therefore, this number should be calculated initially before manufacturing to produce the bars with the required fiber volume fraction. The effective cross-sectional area of each yarn, A_y, was estimated as 1,10 mm^2, 0,16 mm^2, and 0,20 for glass, aramid, and carbon fibers respectively. The effective cross-sectional area of the used fibers yarns was calculated using the equation:

$$A_y = \frac{W_y}{r \times l}$$

Where A_y is the effective cross sectional area of the yarn, W_y is the weight of the used fiber yarn, r is the fiber density, and l is the length of yarn. The relation between fiber volume fraction and number of yarns used in rebars manufacturing was obtained using the equation:

$$V_f = \frac{n \times A_y}{A_b}$$

Where

V_f is the fiber volume fraction of the bars;

n is the number of yarns used in producing the rebar cross section, and A_b is the cross-sectional area of the bar.

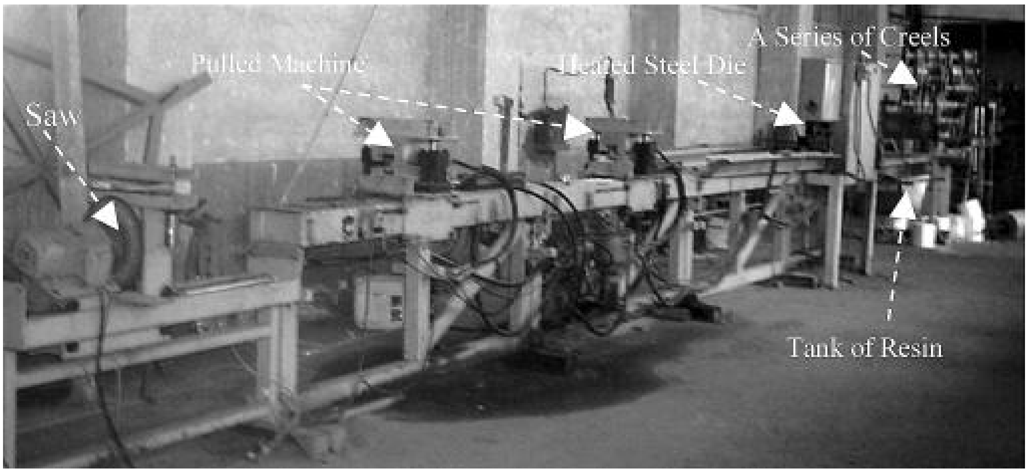

Fig. 5. General layout of pultrusion machine

Table 2

Details of the manufactured bars

Group Code	Fiber Type Used	Specimen Code	No. of Yarns			Fiber Volume Fraction V_f, %		
			Glass	Aramid	Carbon	Glass	Aramid	Carbon
GF Rebars	Glass Fiber	GF	32	–	–	61	–	–
HGAF Rebars	Glass - Aramid Fiber	HGAF 1	29	18	–	55	5	–
		HGAF 2	27	32	–	52	9	–
		HGAF 3	23	61	–	44,5	17	–
HGCF Rebars	Glass - Carbon Fiber	HGCF 1	29	–	14	56	–	5
		HGCF 2	26	–	30	50,4	–	10,6
		HGCF 3	22	–	54	42,6	–	19

Table 3

Unit weight improvement of HFRP-bars

Group	Average unit weight, gm/cm^3	Fiber Volume Fraction V_f, %			V_A or V_C/ V_f , %		Percentage of unit weight improvement, %
		V_G	V_A	V_C	V_A/ V_f	V_C/ V_f	
GF	2,77	61	–	–	0	0	–
HGAF1	2,26	55	5	–	8,33	0	18,41
HGAF2	2,20	52	9	–	14,75	0	20,58
HGAF3	2,08	44,5	17	–	27,64	0	24,91
HGCF1	2,36	56	–	5	0	8,16	14,8
HGCF2	2,2	50,4	–	10,6	0	17,38	20,58
HGCF3	2,14	42,6	–	19	0	30,84	22,74

According to the research program, seven different types of manufactured bars were produced. These manufactured bars are divided into three groups, Table 2. The produced bars have a constant diameter of 8,5 mm. According ACI 440 [2], the suitable fiber volume fraction (V_f) ranges from 50 % to 70 %. So, an average fiber volume fraction (V_f) of about 61 % was used for bars production in this research. Table 2 shows the fiber volume fractions (V_f) and number of yarns for the different produced bars.

Unit weight of HFRP rebars

The purpose of this test is to estimate the unit weight of the manufactured bars. The unit weight of the HFRP-bars is calculated using the equation:

$$g = \frac{4W}{p d^2 L_s}$$

Where γ is the unit weight of the HFRP bars, W is the total weight, d is the diameter of HFRP bar, and L_s is the Specimen length. The percentage of unit weight improvement with respect to the Glass FRP bars unit weight for the different ratios of Aramid or Carbon fiber to the total fiber volume fraction in the produced bars is presented in Table 3.

Tensile strength test

Test specimens

Because of the brittle nature of the FRP bars, they usually fail in the gripped zones when tested in tension leading to inaccurate results. Therefore, the design and development of the test specimens should include suitable gripping mechanism to assure that the failure takes place away from the gripped zones. In this research the special precautions mentioned in ACI-440 [4] were applied. The precautions are to use steel tube end anchors on both ends of the tested bars to allow for uniform distribution of the load applied from the testing machine to the test

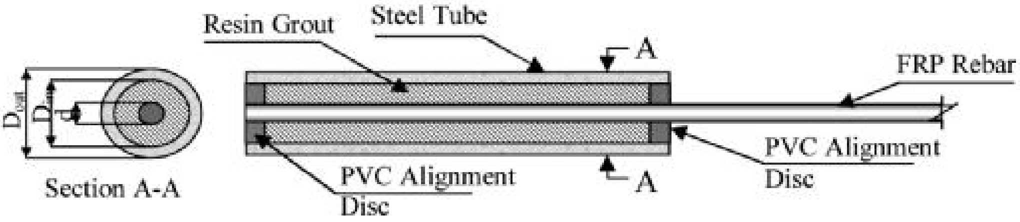

Fig. 6. Details of the used anchorage system

Fig. 7. Dimensions of a typical test specimen

Table 4

Experimental Test Results

Specimen Code		Average Ultimate Load, Ton	Average Ultimate strength, kg/cm^2	Average Modulus of Elasticity, GP	Average Ultimate Strain, %
GF		6,89	12142	41,43	3,03
HGAF	1	6,35	11190	44,29	2,87
	2	6,43	11331	45,65	2,76
	3	6,62	11666	50,07	2,67
HGCF	1	6,13	10803	50,47	2,47
	2	6,43	11331	55,74	2,85
	3	5,85	10309	65,35	2,81

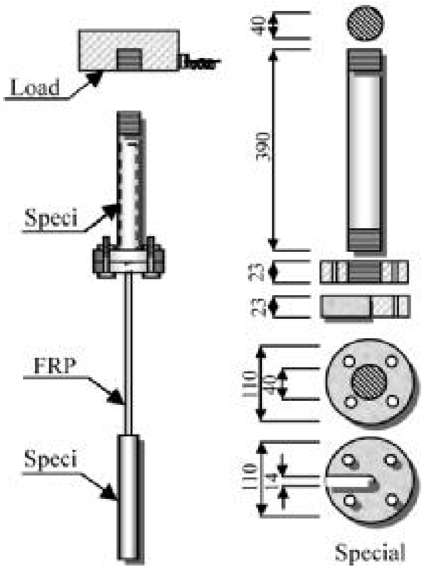

Fig. 8. Schematic diagram of special assembly details and dimensions [4]

Fig. 9. Test setup and instrumentations

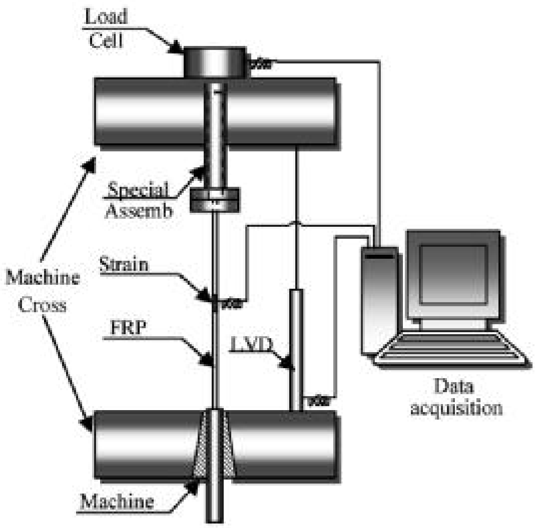

Fig. 9 (cont.)

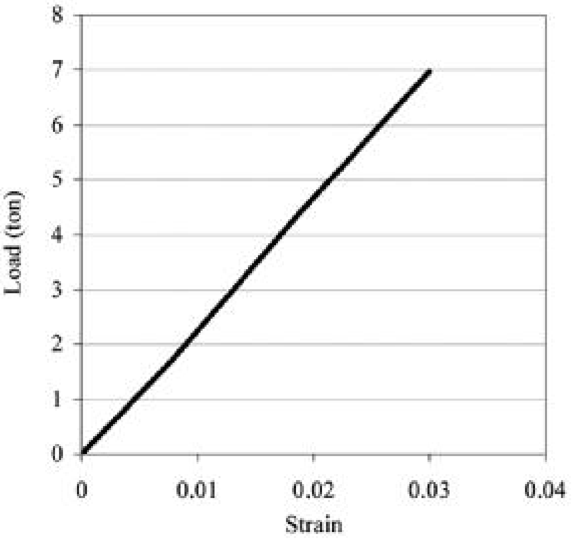

Fig. 10. Load-Strain relationship for pure glass fibers, $V_f = 61$

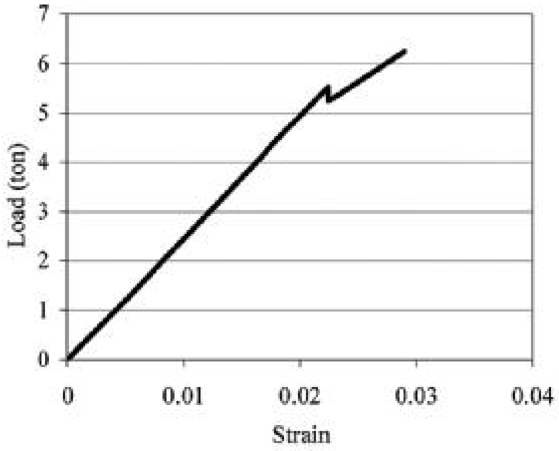

Fig. 11. Load-strain relationship for aramid-glass (HGAF 1), $V_G = 55$ %, $V_A = 5$ %

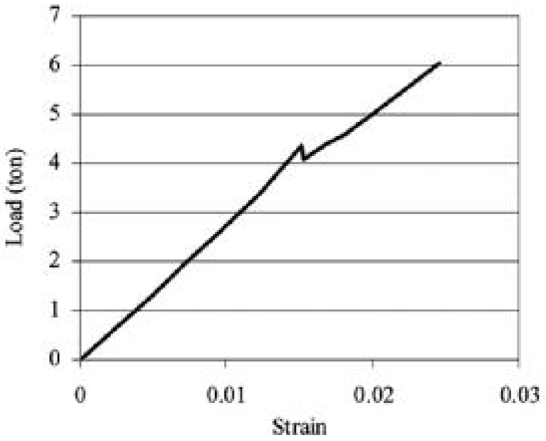

Fig. 12. Load-strain relationship for carbon-glass (HGCF 1) $V_G = 56$ %, $V_C = 5$ %

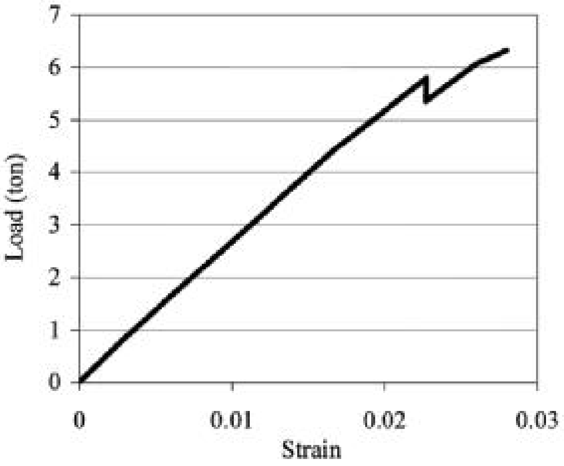

Fig. 13. Load-strain relationship for aramid-glass (HGAF 2), $V_G = 52$ %, $V_A = 9$ %

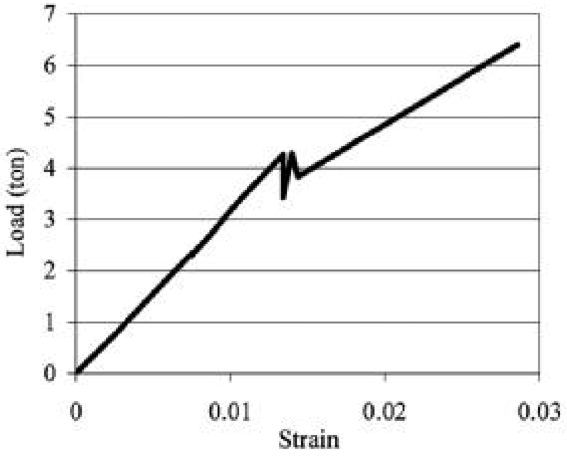

Fig. 14. Load-strain relationship for carbon-glass (HGCF 2), $V_G = 50{,}4$ %, $V_C = 10{,}6$ %

specimen. The anchorage system, Fig. 6, composed of a steel tube of 28 mm and 20 mm external and internal diameter, respectively. The steel tube was filled with a high performance resin grout to assure good bond between the bar and the steel tube. Figure 6 shows a schematic diagram of the details of the used anchorage system. Figure 7 shows a schematic diagram and the dimensions of typical test specimen.

Test setup

In order to satisfy the minimum requirements for the tension test specimens as recommended by ACI-440 [4], the test specimens were provided by a special assembly that consists of steel tube with screwed ends to attach the specimen anchor to the load cell as shown in Fig. 8. Figure 9 shows a schematic diagram of the test setup for tensile characteristic measurements.

A universal testing machine of a capacity of 500 kN was used. A steel anchor tube of external and internal diameters of 28 mm and 20 mm respectively, and 350 mm length was used and constructed so as to transmit loads axially from the testing machine to the test specimen. Load cell of an accurate capacity of 50 N and 240 kN was used and connected to the Data acquisition system that was used for collecting all required readings during the test.

Test results

A summary of test results are presented in Table 4. The load-strain relationships of tested bars are given in Fig. 10 through Fig. 16. It was observed that the failure of all test specimens took place in the middle third of the specimens‘ length where the fibers broke and the damage spread throughout the specimens‘ length, as shown in Fig. 17. With reference to Fig 10, it is clear that GFRP bars showed linear behavior until failure. The bars also showed a clear brittle failure. For bars manufactured with hybrid aramid-glass fibers with aramid-glass fibers percentages V_G = 55 %, V_A = 5 % (HGAF1), Fig. 11, the bars showed linear behavior until about 87 % of the ultimate load, where a sudden drop in the load-strain curve occurred. Then the load-strain rate was shown to be lower than that before the drop. This behavior indicates little bet ductile behavior compared to that of the pure GFRP bars. Similar behavior was shown by the carbon-glass hybrid fiber bars with V_G = 56 %, V_C = 5 % (HGCF1), Fig. 12, but with better ductile behavior as the load-strain dropped at about 70 % of the ultimate load. Also bars manufactured with aramid-glass hybrid fibers with aramid-glass fibers percentages V_G = 52 %, V_A = 9 % (HGAF2), showed similar behavior as that for HGAF1 bars but with better failure criteria, Fig. 13. Figure 14 indicates that the bars manufactured with carbon-glass hybrid fibers, with fibers percentages V_G = 50,4 %, V_C = 10,6 % (HGCF 2), showed a yielding zone at load about 65 % of the ultimate load, also the load-strain rate was clearly low after yielding. The same behavior was observed for bars manufactured with aramid-glass fibers, with fibers percentages V_G = 44,5 %, V_A = 17 % (HGAF 3), but with higher yield/ultimate loads ratio, Fig. 15. For bars manufactured with carbon-glass hybrid fibers, with carbon-glass fibers percentages V_G = 42,6 %, V_C = 19 % (HGAF 3), the load-strain behavior was linear until a clear yielding occurred at load about 80 % the ultimate load. After yielding, the load-strain rate was clearly low and the load-strain curve deviated clearly towards the x-axis showing a clear semi-ductile behavior, Fig. 16.

Test results as indicated in this section revealed that the aramid and carbon fibers improve the behavior and the ductility of GFRP rebars when used with glass fibers in manufacturing the hybrid fibers-reinforced polymers rebars.

Comparing the load strain curves for the hybrid bars to that of the Glass bars as shown in Figs. 18 and 19 revealed that, the manufactured hybrid bars failed in a kind of semi-ductile manner simulating to some extent the behavior of conventional steel reinforcement. Figures 18 and 19 also indicate that the effect of carbon fibers is more significant than the effect of aramide fibers in improving the behavior and the ductility of the hybrid rebars in this research. Also the enhancement in the behavior and ductility of HFRP rebars due to the increase in the percentage of the carbon fibers in the carbon-glass total content, is more clear compared to similar increase in the aramid fibers perentage in the aramid-glass total content, Figs. 18 and 19.

Modulus of elasticity

Figure 20 shows the effect of the different ratios of aramid and carbon fibers in the total fiber volume fraction on the modulus of elasticity of bars in this research. It is clear from Fig. 20 that, increasing the aramid or carbon ratio in the total fiber volume fraction in tested bars, increases their initial modulus of elasticity compared to that of pure glass rebars. This is because that aramid and carbon yarns have higher modulus of elasticity relative to glass yarns, Table 1. It is also indicated in Fig. 20 that, rebars manufactured using hybrid carbon-glass fibers showed higher modulus of elasticity than those for bars manufactured using hybrid aramid-glass fibers. The increase in the modulus of elasticity for the aramid-glass bars compared to that for pure glass fibers bars was estimated as 6,9, 10,19 and 20,85 % corresponding to percentage of aramid fibers in the total fibers content of 8,33, 14,75 and 27,64, respectively. Also the increase in the modulus of elasticity for the carbon-glass bars compared to that for pure glass fibers bars was estimated as 21,82, 34,54 and 57,74 % corresponding to percentage of carbon fibers in the total fibers content of 8,16, 17,38 and 30,84, respectively.

Summary and conclusions

This paper studies the feasibility of using locally available materials and facilities in producing hybrid FRP

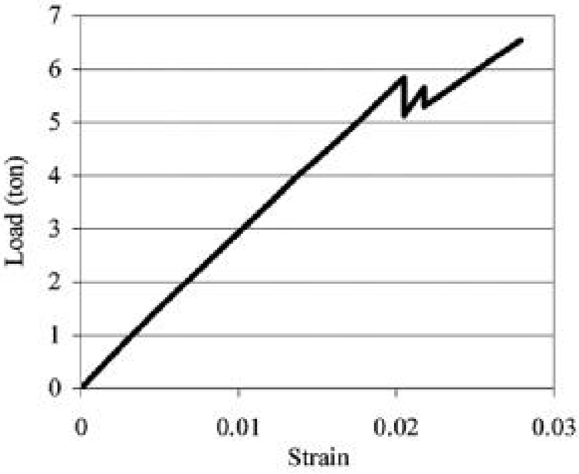

Fig. 15. Load-strain relationship for aramid-glass (HGAF 3), $V_G = 44{,}5\%$, $V_A = 17\ \%$

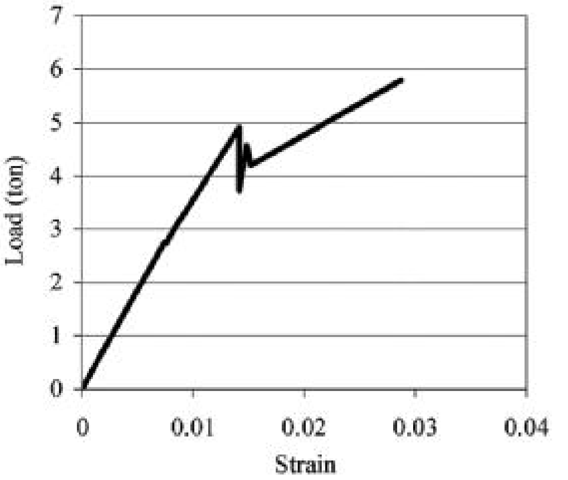

Fig. 16. Load-strain relationship for carbon-glass (HGCF 3), $V_G = 42{,}6\ \%$, $V_C = 19\ \%$

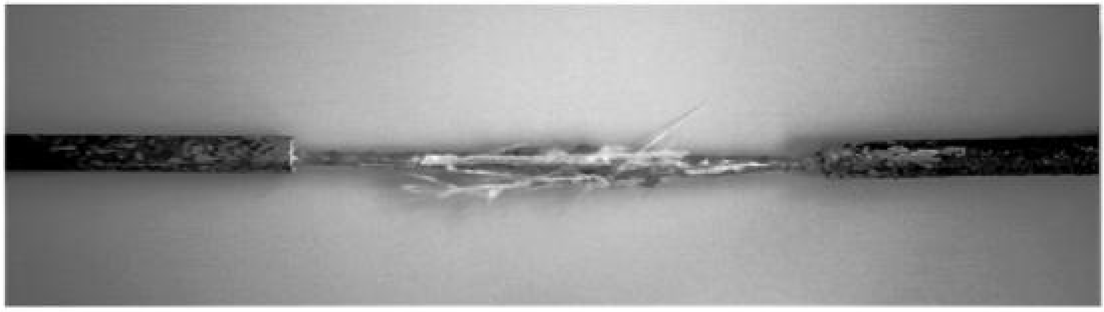

Fig. 17. Typical Failure mode of Tested Rebars

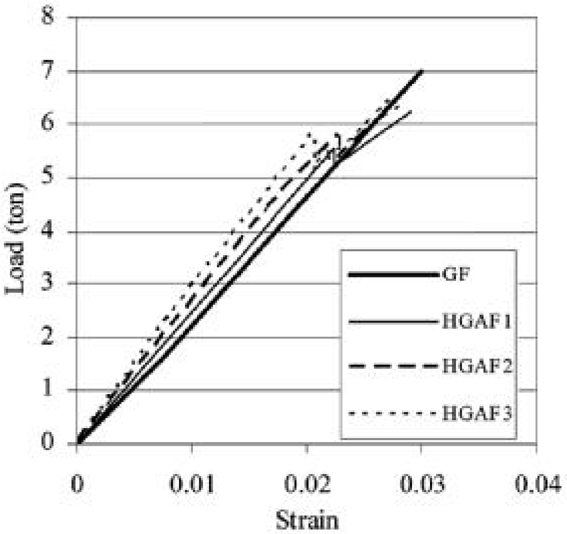

Fig. 18. The Load-strain relationship for aramid-glass FRP rebars with different volume fraction

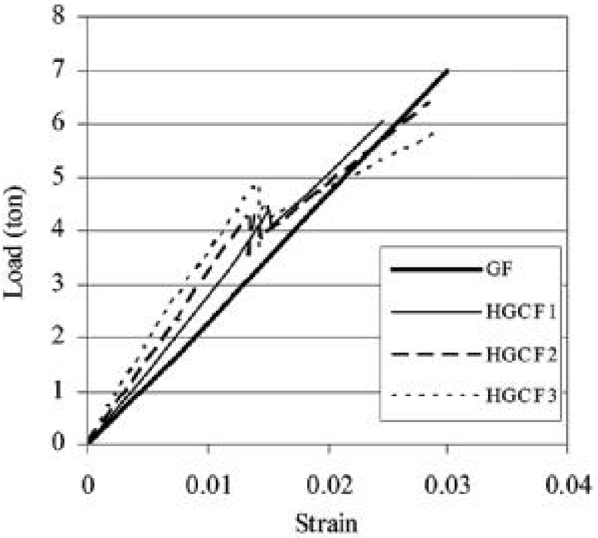

Fig. 19. The Load-strain relationships for carbon-glass FRP rebars with different volume fraction

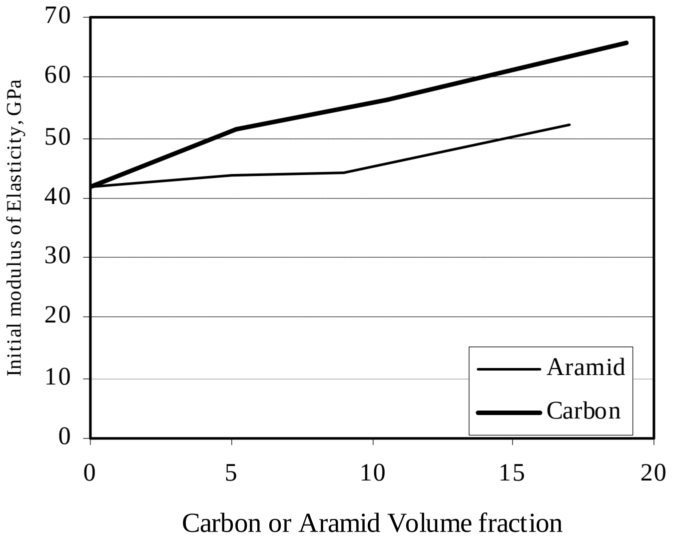

Fig. 20. Effect of aramid and carbon fibers on the initial modulus of elasticity of HFRP rebars

rebars with improved ductility characteristics using glass, carbon, and aramid fibers. Based on the results of the current research, the following conclusions could be drawn:

1. Hybrid fiber-reinforced polymers rebars manufactured using aramid-glass or carbon-glass fibers in this research, have lower unit weight compared to pure glass rebars and improve their behavior and the failure criteria. The percentage in the reduction in the unit weight was estimated as 20 % as an average. Also HFRP rebars showed strength/weight ratio higher than that for pure glass FRP rebars. The increase in the strength/weight ratio was estimated as 20 % and 11 % for aramide-glass and carbon-glass rebars, respectively. The optimum increase in the strength/weight ratio was recorded for aramid-glass rebars with volume fraction of 17 % and 44,5 % for aramid and glass fibers, respectively.

2. Increasing Carbon or aramid volume fraction in total fiber content in hybrid rebars, increases significantly their initial modulus of elasticity, but carbon fibers are more effective than aramid fibers in increasing the initial modulus of elasticity of hybrid rebars. The improvement in the initial modulus of elasticity was estimated as 11 % and 38 % for aramid-glass and carbon-glass hybrid rebars, respectively. The optimum improvement in the initial modulus of elasticity was recorded for carbon-glass rebars with volume fraction of 19 % and 42,6 % for carbon and glass fibers, respectively.

Generally it can be concluded that using the aramid fibers with glass fibers in HFRP rebars is more effective than using carbon fibers in enhancing significantly the rebars strength-to-weight ratio. While the carbon fibers are more effective when used with glass fibers in enhancing the initial modulus of elasticity of HFRP rebars.

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