Development of Innovative HFRP Bars

Kostiantyn Protchenko^{1,}, Elżbieta Szmigiera¹, Marek Urbański¹ and Andrzej Garbacz¹*

¹Warsaw University of Technology, Civil Engineering Department, Lecha Kaczyńskiego St., 16, 00-637 Warsaw, Poland

Abstract. The main factors determining the choice of fiber-reinforced polymer (FRP) materials are the intended use of the designed structure and the environmental conditions in which it will be located. Currently, the FRP-based materials have a variety of applications in the construction industry, from the secondary structural elements of buildings, to a complicated designs, where the only FRPs were used. The advances in FRP technology have spurred interest in introducing innovative hybrid fiber-reinforced polymer (HFRP), which potentially can be used as reinforcing/enhancing material. This paper describes the investigation on newly-developed hybrid fiber-reinforced polymer HFRP bars, which were created by modification of basalt fiber-reinforced polymer BFRP bars in terms of physical substituting of the certain amount of basalt fibers by the part of carbon fibers. Modification is aimed at achieving of better properties in obtained material and simultaneously ensuring cost-effectiveness concept. The investigation includes the preparation and numerical considerations on HFRP bars as well as first attempts of experimental structural testing of innovative HFRP bars.

1 Introduction

Enormous potential exists for application fiber-reinforced polymer (FRP) materials in construction industry to replace conventional materials, which are highly susceptible to corrosive and harsh environments. The practice exists to use FRP-based composite materials for external enhancing (i.e. reinforcing tapes, mats, laminae/laminates etc.), internal reinforcing (smooth, sand-coated, ribbed, mixed type bars), pre-stressing tendons and building elements made entirely from FRP-based materials. Moreover, during the manufacturing stage it is possible to obtain the FRP-based materials of different cross-sectional shapes and material combination that would be difficult or impossible with conventional steel materials [1, 2].

Basically, the selection of FRP materials is associated with applications where their unique characteristics will be the most appropriate corresponding to the situation. FRP reinforcing bars recommend a potentially attractive alternative to steel reinforcing bars. The former are non-corrosive and generally of a higher strength than their steel counterparts [3]. FRP bars have most commonly been used in foundations of buildings,

* Corresponding author: k.protchenko@il.pw.edu.pl

parking garages, applications in walls (where the stiffness of bars is not of high importance), road surfaces, bridge decks, structures associated with high humidity etc.

The main features that distinguish FRP bars from ordinary steel bars are: low/high modulus of elasticity (depending on the type of FRP), linear-elastic behavior until failure, high tensile strength, low weight, increased corrosion resistance, electromagnetic transparency, non-toxicity etc.

The commercially available FRP bars include aramid (AFRP), carbon (CFRP), glass (GFRP) and basalt (BFRP) types. All of the FRP bars exhibit different tensile strength, different Young's modulus, ductility and other characteristics depending on the type of fibers that were used. The cost of producing some types of bars is relatively high and other types in turn does not fulfill required strength characteristics. The optimal solution considering the cost-effectiveness concept is the use of Hybrid Fiber Reinforced Polymer (HFRP) bars.

An extensive research on HFRP bars is being conducted at the Warsaw University of Technology in conjunction with FRP manufacturing company upon the programme of National Centre for Research and Development in Poland. This research aims at characterizing newly developed types of HFRP bars, their mechanical and physical performance as well as their performance in structural systems [4].

The used hybrid fibers were carbon-basalt. The locally produced Hybrid Carbon / Basalt Fiber Reinforced Polymer (HC/BFRP) bars are characterized by better mechanical characteristics than BFRP bars and better cost-efficiency comparing to CFRP bars. Additionally, both types of fibers are characterized by approximately same strain parameters, which was considered as the additional criterion for the fibers selection [5].

The careful examination of physical and mechanical properties of the newly developed HFRP bars is needed with the aim to provide designers with more possibilities regarding an appropriate choice on materials.

2 Testing of Developed HFRP Bars

2.1 The Proposed HFRP Structure

FRP materials are created by synthetic assembly of two or more distinct constituents on a macroscopic scale. The basic constituents of such a material, fibres, resin and sometimes other fillers, are combined in order that final product exploits the best of their individual qualities [6]. HFRP material in context of this research is the material, which has more than one type of fibers as a reinforcement constituent embedded into a single or multiple matrix constituent(s).

It is worth mentioning that characteristics and durability of the final products depends on the following factors:

- The selection and properties of constituents;
- The quality of developed bars (manufacturing process);
- The interphase development (bond behavior).

The HFRP bars described in the research were made by physical substitution of the certain amount of basalt fibers by the part of carbon fibers embedded in epoxy resin. Different levels of fibers substitution were considered before the preparation of final products. The various volume fractions between carbon and basalt fibers (C:B) were proposed: 1:1, 1:2, 1:3, 1:4 and 1:9 with the constant volume fraction of epoxy resin – 20%.

The carbon fibers are characterized by strong anisotropy and were selected due to its high specific strength characteristics in the longitudinal direction. Basalt fibers are characterized by weak anisotropy and the selection of basalt fibers is mainly based on its

environmentally friendly manufacturing process. Table 1 describes properties of constituents used for HFRP bars.

Table 1. Properties of constituents used for HFRP bars.

Material / property	Epoxy resin	Carbon fibers	Basalt fibers
Density (g/cm3)	1.16	1.90-2.10	2.60-2.80
Diameter (µm)	-	7.00	11.2
E11 (GPa)	3.45	232.00	89.00
E22 (GPa)	3.45	15.00	89.00
v12	0.35	0.279	0.26
v23	0.35	0.49	0.26
G12 (MPa)	1.28	24.00	21.70
G23 (MPa)	1.28	5.03	21.70
σ11 (MPa)	55-130	2500	1151.79

Where: Eii is the Young’s modulus along axis i, vij is the Poisson ratio that corresponds to a contraction in direction j on the plane whose normal is in direction i, and Gij is the shear modulus in direction j on the plane whose normal is in direction i, σii is the tensile strength in the direction i.

2.2 Analytical and Numerical Considerations

Analytically, the properties of HFRP bars, including stiffness, strenght etc., in the axial direction can be found using the Rule of Mixtures (ROM) (axial loading - Voigt model) [7]. However, the proposed equation does not consider the location of fibers. Some studies mentioned in [8] suggest that final mechanical properties of HFRP bars can differ basing on the bar configuration, i.e. different location of fibres. Therefore, to evaluate the influence of fibers location on the mechanical properties, the two configurations were analyzed. Figure 1a shows the configuration with carbon fibers in the core region of the bar and Figure 1b shows the bar configuration with carbon fibers located in the near-surface region.

Fig. 1. Considered bar configurations (a) carbon fibers in the core region (b) carbon fibers in the near-surface region.

The numerical simulation of tensile strength test for both bar configurations with various volume fractions was made in Finite Element Analysis (FEA) software ANSYS. The HFRP bars were represented in the form of cylindrical elements with the length 850

mm and diameter 8 mm. The elements consisted of two parts, core region and near-surface layer, which were perfectly interconnected. The constant pressure was applied from the both sides. More detailed information about numerical simulations can be found in [4].

The results were obtained for different bar configurations basing on the location of constituents and their volume fraction. Obtained results indicate a good convergence with analytical considerations, the maximum deviation is 2%. Numerical simulations show that the location of fibres is not of high importance since its influence can be negligible. However, different volume fractions can influence on the final properties at maximum by 74.6%.

2.3 Manufacturing and Structural Testing

As it was described in previous section, the location of fibers does not influence significantly on the final mechanical properties. Therefore, basing on the results, manufacturing company attempted to produce both configurations. However, while placing carbon fibers in the near-surface layer, several technological issues were observed, such as: local scorching or an increased heterogeneity. Consequently, it was decided that carbon fibers would be placed in the core region of the bar.

The tensile test (axial loading) was performed for HC/BFRP bars. The diameter of the developed bars was 8 mm. The volume fraction, which was selected for the producing HC/BFRP bars were C/B: 1:4. The five bars for every samples type were subjected to tensile testing. Additionally, the five BFRP bars were tested as reference bars.

Table 2 describes geometrical characteristics for HC/BFRP and BFRP 8 mm bars and the deviation between expected and physical dimensions.

Table 2. Geometrical characteristics of FRP bars.

Nominal diameter [mm]	Quantity	Diameter	Circumference	Mass	Density
		d_b [mm]	c_b [mm]	m [g]	γ [g/cm ³]
BFRP 8	Means	8.77	27.6	21.9	1.80
	Standard deviation	0.05	0.16	0.13	0.01
HC/BFRP 8	Means	8.32	26.1	20.9	1.92
	Standard deviation	0.03	0.09	0.11	0.02

Due to different behavior of FRP bars in transverse and longitudinal direction the special anchoring at both ends is required to be further used in tensile testing machine. With this aim, two steel tubes with outer diameter of 40 mm, wall thickness of 5 mm and the length of 400 mm each were used. Anchoring tubes parameters has been determined on the basis of previous studies [9]. The spacing between bars and tubes was filled with the adhesive layer.

The tensile strength test was carried out in accordance with ACI 440.3R standard for pultruded FRP bars. The average values of tensile strength (limit stress), f_u , modulus of elasticity, EL , and the limit strain, ϵ_u , for HC/BFRP and BFRP bars were obtained and are shown in the Table 3 and Table 4.

BFRP bars as well as newly developed bars, despite anisotropic properties, showed high tensile strength in longitudinal direction. However, the stiffness characteristics were lower than predicted by analytical and numerical simulations. The samples were destroyed by splitting and the destruction mechanism of bars had a brittle character (Figure 2).

Fig. 2. Destruction of 8 mm diameter HC/BFRP bar.

Table 3. Mechanical properties of HC/BFRP bars of 8 mm diameter.

HC/BFRP Ø8mm	Maximum strength, F_u	Tensile strength, f_u	Tensile strain at rupture, ε_u	Modulus of elasticity, E_L
	[kN]	[MPa]	[%]	[GPa]
Average	77.21	1277.92	1.73	73.89
Standard deviation σ	3.35	55.4	0.07	3.07
Variation	4.34%	4.34%	4.33%	4.15%

Table 4. Mechanical properties of BFRP bars of 8 mm diameter.

BFRP Ø8mm	Maximum strength, F_u	Tensile strength, f_u	Tensile strain at rupture, ε_u	Modulus of elasticity, E_L
	[kN]	[MPa]	[%]	[GPa]
Average	60.03	1103.3	2.52	43.87
Standard deviation σ	1.24	22.87	0.05	0.86
Variation	2.07%	2.07%	2.09%	1.95%

Table 3 and Table 4 describe that for the HC/BFRP bars with 8 mm diameter, the coefficient of variation of all the aforementioned properties was slightly above 4%. However, for the BFRP bars it was approximately 2%.

3 Results and Discussion

Experimental results demonstrated good convergence for the samples of the same type. The density of HC/BFRP bars with the volume fraction C/B: 1:4 was higher by 7% than the density of tested BFRP bars. The modulus of elasticity and tensile strength of HC/BFRP bars were increased by 68.4% and 15.8%, respectively, comparing to BFRP bars. The elongation of HC/BFRP bars was 16% lower, which can be explained by better extension properties of carbon fibers.

However, the properties of materials obtained experimentally were different comparing to the ones that were received numerically or analytically. In comparison to the analytical/numerical investigation, the modulus of elasticity of HC/BFRP bars obtained experimentally was approximately 20% smaller than for BFRP bars. The difference in results can be explained by imperfect technological process. Additionally, some other factors can influence on the final characteristics, such as: an increased heterogeneity, different bond characteristics etc.

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