Compressive Properties of BFRP and HFRP Bars

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Abstract: Durability of steel reinforced structures is one of the leading problems in construction field nowadays. Currently many studies are focused on the possibility of steel reinforcement replacement in concrete structures with a non-corrosive reinforcement, such as FRP (Fiber Reinforced Polymer) reinforcement. This paper presents and compare the results of compression testing of Basalt (BFRP) and a newly developed type of Hybrid FRP (HFRP) bars. The program examined 30 HFRP bars and 30 BFRP bars with a nominal diameter of 8mm and unbraced free-length varying from 50 to 220 mm. Compressive buckling load strength decreased as free length increased, and the modulus of elasticity under compression for diverse unbraced lengths bars slightly differed, but its value was similar to the modulus of elasticity at tensile. In addition, the test results showed that the ultimate compressive strength of non-buckled HFRP bars as a result of axial compression is about 46% of the ultimate strength. The relationships between the compressive buckling load strength and the unbraced length as well as the optimal unbraced length of the bars were determined. Current research is aiming to contribute the optimization of the transverse reinforcement design and the development of standard regulations in the area of elements with such compressed reinforcement.

1. Introduction
Inevitable obstacles, such as deterioration of building materials and their weak structural properties, have lead and forced engineers around the world to develop and implement new, efficient, and economical techniques on reinforcing and repairing structures. Steel bars are still the most commonly used building materials for reinforcing concrete structures, but researchers are working on an new renewable alternative. Fiber Reinforced Polymers (FRP) bars proved to be a potential alternative to steel bars providing high corrosion resistance, good resistance to chemicals, low weight, high strength to weight ratio, a fast and economical way of implementation [1-4].

Basalt FRP (BFRP) bars are made up of basalt fibers bounded together with matrix polymer. Good mechanical properties of constituents combined with cost-effective manufacturing process led to the production of BFRP bars to be used as internal reinforcement for concrete structures. BFRP bars are characterized also by high temperature resistance, good freeze-thaw performance, low elasticity modulus with respect to steel, chemical resistance and high tensile strength [4-6]. Hybrid FRP (HFRP) bars in context of this work might be understood as a combination of two or more fiber filaments together with the matrix polymer. An extensive research is being held in Warsaw University of Technology on an invented type of hybridization, where both basalt and carbon fibers were combined together creating a newly developed hybrid FRP bars. A detailed description on HFRP bars can be found in these companion papers [8-9].
Compression testing of FRP bars can specify the maximum static strength of bars with different constituents and formations. The use of FRP bars in the compression zone was not recommended by most of the norms and standards. Modified ASTM D695-15 [10] test method for rigid plastics recommends to test the sample by placing it between cylindrical heads in a compression device, where the tested sample should have equal diameter and a length twice than that of the bar. Crushing and unintentional rotation at both ends of the bar was not taken into account by this procedure, which affects the strength and deformation of the bar under compression.

In spite of standards restrictions, several compression tests on different types of FRP bars were made showing the importance of FRP bars for reinforced concrete (RC) structures. However, in FRP compression test, compressed elements with composite reinforcement should be designed by different methods than the compressed steel reinforcement. Different spacing of transverse reinforcement should be used [11].

Alajarmeh et al. [12] conducted a study using three high-modulus GFRP bars with different unbraced length and a nominal diameter of 9.5, 15.9, and 19.1 mm respectively. Some of the tests where done using ASTM- D695, where premature splitting was observed due to high-stress concentration at the ends. Some attempts were made to modify this standard procedure by inserting the bar ends in a steel rod. During the preparation of test specimens, hollow steel caps filled with cementations grout were used to restrain the top and bottom ends of the GFRP bars. The results showed that the increase in bar diameter increases the micro-fiber buckling and decreases the compressive-to-tensile strength ratio. Similarly, the failure mode changed from crushing to fiber buckling with the increase of $L_f/d_b$ ratio, where $L_f$ is the unbraced free length of the bar and $d_b$ is its diameter.

Dietz et al. [13] conducted tests on 45 GFRP reinforcing bars, with a diameter of 15 mm and 50–380 mm free (unbraced) length to determine their ultimate strength and compressive modulus of elasticity. Individually, samples were placed into 135 mm long steel cylinders with an external diameter of 50 mm, intended for screwing into the UTM heads of the testing machine. An opening with 65 mm long and 17.5 mm in diameter was drilled in the center of each threaded cylinder so that any possible rotation of the sample ends would not lead to uncertainty of the results. GFRP samples with a ratio of free bar length to diameter $L_f/d_b < 7.33$ ($L_f < 110$ mm) were destroyed by crushing. The second failure mode for samples with $7.33 < L_f/d_b < 14$ of free length was a combination of crushing and buckling failures. For samples with free length of $L_f > 210$ mm ($L_f / d_b > 14$), the failure mode consisted of almost clean buckling of the free length bar. Based on the limited tests of the three samples, it was found that the modulus of elasticity under compression is approximately equal to the modulus of elasticity under tension. In addition, it was found that for unbuckled reinforcing bars with a free length of $L_f < 110$ mm, the ultimate compressive strength is about 50% of the final tensile strength.

Tavassoli et al. [14] conducted a study on nine circular concrete columns, reinforced with GFRP bars under simulated cyclic loading showing that the columns had a significant strength and ductility. The crushing of the compressed concrete was first to maintain followed by the longitudinal crushing of GFRP bars. Moreover, a part of the study was dedicated on testing 15 GFRP bars with 25mm diameter and various unbraced lengths from two different manufacturers. Free lengths specified based on the spiral pitch of the studied concrete columns, it varied between 50 to 275 mm, which gives the ratio of unbraced length to diameter of 2 to 11. Similar to Dietz method the samples were also placed in a steel cylindrical tube that holds GFRP bars in the machine, showing as a result that the compressive strength of GFRP bar is about 50% of its tensile strength, and its modulus of elasticity in compression is similar to the one received in tension [15].

Current research is focused on the investigation of compressive properties of BFRP and HFRP bars with nominal diameter of 8mm and unbraced free lengths between 50 to 220 mm showing the ways FRP bars acts under axial load depending on the free length and the type.
2. Hybridization concept and HFRP bars
Processing of hybrid bars is analogous to the process of producing of any other commercially available FRP bars, where a part of fibers is physically substituted with another fibers type [16]. The chosen constituents were: basalt and carbon fibers (low strength LS type) and epoxy resin. Carbon fibers (LS) were chosen because of its lower cost and its close extension parameters in comparison to basalt fibers [16].

Upon failure, carbon fibers in HFRP are the first to fail transferring the load to the basalt fibers. Carbon fibers can be characterized as rigid, however can be relatively expensive, at the same time basalt fibers are less expensive but do not have the carbon stiffness. For the aim of increasing stiffness, some basalt fibers are replaced with carbon fibers. The value of elasticity modulus is estimated taking into account the volume fraction of both fibers and the epoxy resin. Various combinations with different volume fractions have been checked during analytical consideration and numerical considerations, specifically the volume fractions were Carbon-to-Basalt [C:B]: 1:1; 1:2; 1:3; 1:4 and 1:9. The volume fraction of the used epoxy resin should be not less than 20% to ensure bonding. Analytical considerations, which were based on Voigt model, do not take into account the fiber distribution in the bar. Hence, it was decided to perform a numerical simulation with different configurations of fibers by finite element methods (FEM) in the software ANSYS® Academic Research Mechanical, Release 16.2 (Ansys Inc., Canonsburg, PA, USA) [17].

From the numerical analysis, it was found that the distribution of fibers does not play significant role as the volume fraction. Therefore, for the experimental phase HFRP bars were made up from carbon fibers, basalt fibers (with the volume ratio C:B - 1:4) and epoxy resin. Carbon fibers were placed in the core region because of the burning of carbon fibers in the near-surface region upon producing. The bars were characterized by higher stiffness and in general were having better mechanical properties [8, 9, 16]. The properties of HFRP bars and BFRP bars obtained experimentally are shown in the table 1.

| Table 1. Mechanical properties of HFRP and BFRP bars of 8 mm diameter. |
|---------------------------------------------------------------|
| **Type of bars** | **BFRP bars** | **HFRP bars** |
|                  | Physical size |            |
|                  | Symbol | Maximum force | Tensile strength | Tensile strain at rupture | Modulus of elasticity | Maximum force | Tensile strength, | Tensile strain at rupture | Modulus of elasticity |
|                  | Unit | (kN) | (MPa) | (%) | GPa | (kN) | (MPa) | (%) | GPa |
| Average          | F_u  | 60.03 | 1103.3 | 2.52 | 43.87 | 77.21 | 1277.92 | 1.73 | 73.89 |
| Standard deviation σ | f_u  | 22.87 | 0.05 | 0.86 | 3.35 | 55.4 | 0.07 | 3.07 |
| Variation        | ε_u  | 2.07% | 2.07% | 2.09% | 1.95% | 4.34% | 4.34% | 4.33% | 4.15% |

3. Research program
An experimental buckling load strength tests were done on BFRP and HFRP bars in accordance to standard ASTM D695-15 with some modifications. The bars were tested in ZD20 (WPM, Leipzig, Germany) testing machine with a maximum load of 200 kN.

3.1. Materials utilized for the work
The tests were conducted on 30 HFRP bars and 30 BFRP bars, 5 samples per different unbraced free length with an equivalent diameter of \( d_b = 8.32 \) mm for BFRP bars and \( d_b = 8.77 \) mm for HFRP bars.

The term “free length” - \( L_f \) means the distance between sample anchorages, where the value of the measuring length was taken the diameter of the bar as \( L_f = n \times d_b \), \( n \) values were taken differently for each type of bar (table 2).
Table 2. Number of tested samples

| $L_f$ – free length (mm) | $L_f/d_b$ (--) | Number of samples tested |
|--------------------------|---------------|--------------------------|
|                          |               | BFRP bars | HFRP bars |
| 50                       | 6             | 5          | 5          |
| 85                       | 10            | 5          | 5          |
| 120                      | 14            | 5          | 5          |
| 170                      | 20            | 5          | 5          |
| 185                      | 22            | 5          | 5          |
| 220                      | 26            | 5          | 5          |

3.2. Experimental program description

A relationship between buckling load strength and the non-anchored length of FRP bars is a necessity where the free length of FRP bars may vary from one column to another depending on the spacing of stirrups taken by the designer. Such relationship allows enhance transverse reinforcement spacing, which affects the possibility of having local buckling in longitudinal reinforcement of FRP.

BFRP and HFRP bars were tested taken from the same batch ensuring uniform material properties, total length of the samples of each of the specimens made of BFRP bars and HFRP bars respectively, was $L = L_a + L_f + L_a$. The equivalent bar diameter was determined as an average value according to procedure B1 of the ACI 440.3R standard [18]. $L_a$ is the length of anchors placed at both ends of the bars with longitudinal dimension of 120 mm long steel sleeves and an external diameter of 42 mm.

Using a special adhesive with a hardener (ensured by developed resin mix with additives) the bars were centrally fixed to the sleeve, at first the bar was anchored in one sleeve after the connection was cured the other end of the tested specimen was anchored (figure 1).

![Figure 1](image)

(a) (b)

**Figure 1.** Specimen preparation (a) anchoring at one end, (b) steel sleeves at both ends.

In the aim of absorbing and transferring compressive force, anchorages in the sleeves were applied preventing degradation of the bar ends. In addition, anchorages helped to prevent the movement of the bar during test. Avoiding unexpected crushing inside the sleeve, 16 mm diameter opening have been made along their entire length. Before installing strain gauges placed oppositely in the half free-length of the samples, the surface of the bars was ground and cleaned to eliminate errors and obtain approximate values. In the next stage two strain gauges (model RL20 Techno-Mechanik, Gdansk, Poland) were added for recording data, one with length of 30 mm and other of 20 mm and a gauge resistance of 120 Ω.

Upon measuring, the tested samples were placed in the center of the test machine ensuring clean compression load. To center the position of the bar properly, centering tube was used. Opening occurred in both sides of the tube along longitudinal axis was allowing the measurement and observation of the sample (figure 3).
Avoiding accidental eccentrics, the anchored sample was placed at the bottom of a steel round centering plate allowing its rotation and self-centering operation. The load of the sleeve on the specimen is neglected since it was very low in comparison to the compressive load applied. In case of compressive tests and due to the high impact of transverse buckling load strength, 100 MPa/min load degree was taken so that the total demolish of the sample can occur before seven minutes. When destruction occurs outside the free length zone another sample from the same batch was taken.

4. Results and discussion

The compressive strength of HFRP and BFRP bars was determined according to equation:

\[ f_{f,e} = \frac{F_u}{A_{f,min}} \]  

where:

- \( F_u \) - is the maximum force registered during the test
- \( A_{f,min} \) - is the minimum bar diameter measured immediately before installing the strain gauges on the surface of the bar being tested.

4.1. Compressive (buckling load) strength of BFRP bars

During testing, several destruction modes were distinguished:

1. Mode 1: For specimens with an unbraced free length \( L_f < 85 \text{ mm} \) \((10d_b)\) failure occurred due to the shear of the bar for smaller free lengths. The load decreased rapidly after the bar was damaged and the damage occurred in the central part of the unbraced free length in this group of samples (figure 3a).
2. Mode 2: For specimens with the unbraced free length in the range from \( 10d_b \) to \( 12d_b \), the bars slightly buckled in the final buckled phase, then fiber groups accumulated split leading to a loss in load capacity (figure 3b).
3. Mode 3: For a specimen with unbraced free length greater than \( 12d_b \), buckling obtained at the final phase because of the loss in load capacity due to partial breaking of some fibers and detachment of the epoxy resin (figure 3c).
Figure 3. Failure modes of BFRP bars (a) crushing of the 6$d_b$ free length specimen, (b) buckling with crushing a 12$d_b$ free length specimen, (c) buckling of a 26$d_b$ free length specimen

The obtained values of the average compressive (buckling load) strength of the bars with various values of free lengths presented in table 3.

Table 3. Compression and tension characteristics of BFRP bars.

| $L_f/d_b$ | $L_f$ (mm) | $f_{fc}$ (MPa) | CoV (%) | $f_{fc}/f_{ft}$ | $E_{fc}$ (GPa) | $E_{fc}/E_{ft}$ |
|----------|-----------|----------------|--------|----------------|---------------|----------------|
| 6        | 50        | 375.71         | 6.32   | 0.34           | 41.79         | 0.95           |
| 10       | 85        | 475.43         | 4.27   | 0.43           | 49.87         | 1.14           |
| 12       | 100       | 429.57         | 2.83   | 0.39           | 42.61         | 0.97           |
| 20       | 170       | 184.26         | 5.32   | 0.17           | 45.16         | 1.03           |
| 22       | 185       | 182.47         | 9.27   | 0.17           | 50.45         | 1.15           |
| 26       | 220       | 143.95         | 9.86   | 0.13           | 51.69         | 1.18           |

Column 1 shows the unbraced length $L_f$ as times the equivalent diameter of the bar $d_b$. The compressive strength, $f_{fc}$, was compared with the tensile strength, $f_{ft}$, and the modulus of elasticity under compression, $E_{fc}$, with the tension modulus of elasticity $E_{ft}$, for BFRP bars. According to above results the group of bars which were damaged due to crushing ($L_f < 10d_b$), the stress-strain relationships observed were linear and close to each other for different samples in the same group (figure 4a).

Figure 4. Stress-Strain relationship of BFRP bars (a) $L_f = 6d_b$, failure by crushing, (b) $L_f = 12d_b$, buckling with crushing (c) $L_f = 22d_b$, buckling failure (T1, T2, T3 strain gauges reading, Tm - average strain)

For specimens with $L_f$ in the range from 10$d_b$ to 12$d_b$, and as the free length is increasing an increase in strain difference was observed. This occurrence was associated with method of failure consisting from crushing with slight buckling of the bar (figure 4b).
For specimens with unbraced lengths $L_f > 12d_b$ full buckling of bars were significantly obtained leading to a reduction in compressive strength of the specimens as unbraced length increased (figure 4c).

Linearity of the modulus of elasticity, $E_{fc}$, was determined by dividing the difference of stresses by the difference of strains for the values of 0.5 and 0.2 of the breaking force. The tangent of the secant inclination passing through the two mentioned points is the determined modulus. Due to the anisotropic structure of basalt fibers, the modulus of elasticity under compression will be slightly different from the tension modulus of elasticity for BFRP bars.

4.2. Compressive strength of HFRP bars

Similarly, three different failure modes of HFRP bar samples were distinguished:

1. Mode 1: As in HFRP bars the destruction of the bars ($6d_b$) occurred as a result of splitting individual fibers and separating of epoxy resin. Bar failure is related to the shear of the bar for smaller free length (figure 5a).
2. Mode 2: In samples of intermediate length ($10d_b$, $14d_b$), the onset of failure occurred as a result of buckling. Sustain loading made that the fibers were simultaneously split and as a result the tested bars were crushed (figure 5b).
3. Mode 3: This mode of failure occurred in samples with unbraced free length of $22d_b$ and $26d_b$ as a result of buckling mixed with delamination of the individual fibers of the tested bars (figure 5c).

**Figure 5.** Failure mode of HFRP bars with a diameter of 8 mm (a) $L_f = 6d_b$, failure by crushing the sample, (b) $L_f = 14d_b$, buckling and crushing of the sample, (c) $L_f = 22d_b$, buckling of the sample.

HFRP bar with a free length of $6d_b$ (figure 5a) shows a damage due to crushing on a free length section, usually the damage occurs in the middle of the free length of bars.

As for bars with free length of $14d_b$ the damage occurs as a result of slight buckling followed by a crushing (figure 5b). Moreover, the failure mode of the bars exceeding the free length of $14d_b$ consisted of buckling only without any crushing while achieving of maximum compressive strength. The stress-strain diagram of bars with failure mode 1 were analogue and slight difference was observed concerning the values of modulus of elasticity obtained. It should be noted that for some samples with a free length above $20d_b$ at a maximum load, there were no signs of visible damage on the bar surface.

The stress-strain relationship for compressed bars was determined by stresses in accordance to eq.1 and strain was observed as mean strain value recorded during the test from two strain gauges attached on opposite sides in the middle of the sample. The buckling load strength of HFRP bars decreases with the increase of the unbraced free length of the bar. Buckling load strength (compressive strength) of tested HFRP bars was compared with the tensile strength of the bars with same nominal diameter of 8 mm. The compressive strength obtained was 46% of HFRP tensile strength (for $6d_b$ free-length), decreased to 15% as the anchor length increases (table 4, column 4). The average deformation values
for the sample are shown in table 4, column 5. During compression of the deformation ($\varepsilon_{uc}$), in terms of absolute value, they reach from 1/3 to 2/3 of the tensile deformation ($\varepsilon_{ut}$), with no apparent effect of free length on the deformation value (table 4, column 7).

HFRP samples with free length of 6db and 10db, the stress-strain curves continued rising till crushing, the relationship were linear and characterized by high consistency (figure 6 a-b). The bar failure happens only on the free length of the samples with a sudden decrease in the load upon failure. As for bars with 14db free length the indications of the opposite strain gauges were increasingly divergent (figure 6 a-b).

**Table 4.** Compression and tension characteristics of HFRP bars

| $L_f$ (mm) | $f_{fc}$ (MPa) | CoV | $f_{fc}/f_{ft}$ | $\varepsilon_{uc}$ (%) | CoV | $\varepsilon_{uc}/\varepsilon_{ut}$ | $E_{fc}$ (GPa) | $E_{fc,ave}$ (GPa) | $E_{fc,min}$ (GPa) | $E_{fc,min}/E_{fc,0.2}$ |
|-----------|---------------|-----|----------------|------------------------|-----|-----------------------------|--------------|----------------|----------------|-------------------|
| 50        | 583.60        | 28.13 | 0.46          | 9.01                   | 0.42 | 0.52                        | 73.37        | 73.68          | 73.46          | 0.99              |
| 85        | 516.43        | 23.55 | 0.40          | 6.06                   | 0.30 | 0.35                        | 78.67        | 82.75          | 81.08          | 0.95              |
| 120       | 439.12        | 20.99 | 0.34          | 6.95                   | 0.31 | 0.40                        | 83.89        | 82.41          | 81.65          | 1.00              |
| 170       | 289.48        | 23.85 | 0.23          | 7.73                   | 0.62 | 0.45                        | 78.18        | 78.22          | 77.75          | 1.00              |
| 185       | 296.18        | 25.74 | 0.23          | 12.49                  | 1.15 | 0.72                        | 71.11        | 73.02          | 72.07          | 0.98              |
| 220       | 195.68        | 18.86 | 0.15          | 7.31                   | 0.72 | 0.42                        | 81.26        | 82.34          | 81.55          | 0.99              |

**Figure 6.** Stress–strain relationship (a): $L_f = 6d_b$ crushing of the specimen (b): $L_f = 10d_b$ crushing the sample (c): $L_f = 14d_b$ significant buckling followed by crushing.

**Figure 7.** Stress–strain relationship (absolute value) (a) $L_f = 20d_b$ buckling without visible crushing, (b) $L_f = 22d_b$ buckling without crushing, (c) $L_f = 26d_b$ buckling without visible crushing.

In compression, the values of the modulus of elasticity obtained were approximately similar or slightly higher than those obtained under tension (table 4, column 12). Average values of modulus of elasticity shown in table 4, column 8. For specimens with a greater unbraced free length ($L_f > 14d_b$), stress-strain readings differs which in turn affects the estimation of the elastic modulus (figure 8, a-c).
Modulus of elasticity under compression can be calculated using several ways. First it can be determined based on B2 procedure of the standard ACI 440.3R-12 used for tension bars, where the elastic modulus, \( E_{fc} \) (table 4, column 8) is determined as a ratio of the difference in stress and strain for the values 0.5 and 0.2 of the ultimate force. In other words, it is the tangent of the initial inclination through the two stated points. Different way of elastic modulus calculation is presented in (table 4, column 9) is to calculate the average modulus of elasticity \( E_{fc,ave} \) (table 4, column 9) based on subsequent readings of stress and strain in the range from 0.2 to 0.5 of the ultimate force. Results using this method of calculation are slightly higher than the previous one. The third way of elastic modulus calculation is to assess the minimum value of the tangent modulus of elasticity, \( E_{fc,min} \) (table 4, column 10) using the same range of ultimate force.

The relationship between elastic modulus and the stress for HFRP bars with short and long non-anchored length shown in (figure 8, a-c) respectively. Moreover (figure 8, b) shows a comparison of the tangent tensile modulus of elasticity, \( E_{ft} \), and the compressive elasticity modulus, \( E_{fc} \), for the entire range of absolute stress values (from 0.1 to 1.0 ultimate stress) \( f_{ut} \) and \( f_{uc} \). The tensile tangent modulus of elasticity increases as the load increase due to increase stiffness, when tensioning, however, the compression tangent modulus decreases with the increase in load related to mechanism of micro buckling of the bar. Therefore, minimum tangent modulus of elasticity, \( E_{fc,min} \), is considered as the best value for defining the stiffness for the bars under compression. Hence, the compressive modulus of elasticity of HFRP bars can be calculated based on the modulus of elasticity in tension.

5. Conclusions
The research on BFRP and HFRP bars with nominal diameter of 8 mm showed that the optimal free unbraced length of the bars can be established for which the ultimate compressive strength (buckling load strength) reaches its maximum value while meeting the non-buckling condition. Knowledge of the dependence on buckling load strength is of practical importance because it allows determining the optimal spacing of stirrups in RC compressed elements.

For BFRP bars, the compressive buckling load strength, \( f_{fc} \), depending on the free unbraced length has been exposed to several changes before reaching the optimal value according to the polynomial curve (for \( L_f < 85 \) mm) shown in crushing phase then the linear relationship (for \( L_f < 125 \) mm) achieved in the transition phase. As for HFRP bars, the optimal value was reached directly where the compressive buckling load strength decreases monotonically as free unbraced length increases. During the three obtained phases a linear relationship is obtained with correlation of \( R^2 = 0.99 \) allowing a simple selection of spacing in transverse reinforcement depending on the effort of compressed HFRP bars.

Moreover, the substitution of basalt fibers with carbon fibers (with the volume ratio C:B - 1:4 indicates a clear difference in the increased values of compressive strength (55%) and modulus of...
elasticity $E_c$; e.g., for bars with free length $6d_b$ compressive strength increased from 375.7 to 583.6 MPa and modulus of elasticity from 41.79 to 73.46 GPa in BFRP and HFRP respectively.

For non-buckled BFRP and HFRP bars the values of the modulus of elasticity under compression $E_{f,c}$ are similar to those under tension, $E_{f,t}$. For bars with larger free lengths, the tangent modulus of elasticity under compression reached slightly higher values.

The minimum value of the tangent modulus of elasticity for the range of 0.2–0.5 ultimate load should be taken as the representative value of elasticity modulus considering that $E_{f,c,min}$ is the best measure for stiffness for bars due to buckling load that should be taken into account while designing. Furthermore, according to the authors respectively, both BFRP and HFRP bars can be used as a compressive reinforcement but under special conditions. Further researches should be carried out on the remaining bar diameters for both HFRP and BFRP bars used to propose a general relationship for the design of reinforcement in the compression zone.

References
[1] Danraka M N, Mahmood H M, Oluwatosin O J and Student P 2017 Intern J of Eng Science 7 (6) p 13199
[2] Protchenko K, Wlodarczyk M and Szmigiera E 2015 Proc Eng 111 pp 679–686 http://doi.org/10.1016/j.proeng.2015.07.132
[3] Garbacz A, Szmigiera E, Protchenko K and Ubarański M 2018 International Congress on Polymers in Concrete (ICPIC 2018): Polymers for Resilient and Sustainable Concrete Infrastructures, Springer p 653-658 https://doi.org/10.1007/978-3-319-78175-4_83
[4] Protchenko K and Szmigiera E 2020 Materials 13 (5) p 1248 http://doi.org/10.3390/ma13051248
[5] Elgabbas F, Vincent P, Ahmed E A and Benmokrane B 2016 Compos Part B-Eng 91 205-218. http://doi.org/10.1016/j.compositesb.2016.01.045
[6] Ubarański M, Łapko A and Suprynowicz K 2016 Solid State Phenomena 240 p 55–60 http://doi.org/10.4028/www.scientific.net/SSP.240.55
[7] Protchenko K, Szmigiera E, Ubarański M, Garbacz A, Narloch P and Lesniak P 2019 IOP Conf Series: Mat Sci and Eng 661 p 012081 http://doi.org/10.1088/1757-899X/661/1/012081)
[8] Protchenko K, Szmigiera E, Ubarański M and Garbcz A 2018 MATEC Web of Conf. 196 p 04087 http://doi.org/10.1051/matecconf/201819604087
[9] Protchenko K, Dobosz J, Ubarański M and Garbcz A 2016 Czasopismo Inżynierii Lądowej, Środowiska i Architektury, JCEEA 63 1/1 pp 149–56
[10] ASTM D695—15: Compressive Properties of Rigid Plastics; ASTM International: West Conshohocken, PA, USA, 2015
[11] Ubarański M 2020 Materials 13 (8) p 1898 https://doi.org/10.3390/ma13081898
[12] Alajarmeh O S, Manalo A C, Benmokrane B, Vijay P V, Ferdous W and Mendis P 2019 Constr Build Mater 225 pp 1112–26 https://doi.org/10.1016/j.conbuildmat.2019.07.280
[13] Deitz D H, Harik I E and Gesund H H 2003 J. Compos. Constr. ASCE 7 pp 363–6 http://doi.org/10.1061/(ASCE)1090-0268(2003)7:4(363)
[14] Tavassoli A 2013 Thesis: Behaviour of GFRP-reinforced concrete columns under combined axial load and flexure (Toronto: University of Toronto) ON Canada p 201
[15] Khorrramian K and Sadeghian P 2019 J Test Eval 49 pp 1–28 http://doi.org/10.1520/JTE20180873
[16] Szmigiera E, Protchenko K, Ubarański M and Garbcz A 2019 Arch of Civ Eng 65 (1) pp 97–110 http://doi.org/10.2478/ace-2019-0007
[17] ANSYS® Academic Research Mechanical, Release 16.2, Help System, Coupled Field Analysis Guide; ANSYS, Inc.: Canonsburg, PA, USA, 2016
[18] 440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures, ACI, 2012