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Research paper

Shear strength testing of basalt-, hybrid-, and nano-hybrid fibre-reinforced polymer bars

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Abstract: Over the past decades, using of sustainable materials in construction is a challenging issue, thus Fibre Reinforced Polymers (FRP) took the attention of civil and structural engineers for its lightweight and high-strength properties. The paper describes the results of the shear strength testing of three different types of bars: (i) basalt-FRP (BFRP), (ii) hybrid FRP with carbon and basalt fibres (HFRP) and (iii) nano-hybrid FRP (nHFRP), with modification of the epoxy matrix of the bar. The hybridization of carbon and basalt fibres lead to more cost-efficient alternative than Carbon FRP (CFRP) bars and more sustainable alternative than Basalt FRP (BFRP) bars. The BFRP, HFRP and nHFRP bars with different diameters ranging from Ø4 to Ø18 mm were subjected to shear strength testing in order to investigate mechanical properties and the destruction mechanism of the bars. Obtained results display a slight downward trend as the bar diameter increase, which is the most noticeable for HFRP bars. In most of the cases, BFRP bars were characterized by greater shear deformation and less shear strength compared to HFRP and nHFRP bars. Performed testing may contribute to comprehensive understanding of the mechanical behavior of those types of FRP bars.

Keywords: Hybrid FRP bars, Fibre-Reinforced Polymers (FRP) bars, nHFRP bars, shear testing, composite bars

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1. Introduction

Throughout last decades, researchers have experimented different materials in various context and Fibre Reinforced Polymers (FRP) proved to be an applicable material for strengthening and reinforcing of concrete structures [1, 2]. FRP materials have a wide range of applications in construction, such as reinforcement of concrete, formwork, modular structures, bridge decks, rammed earth lintels and external reinforcement for strengthening and seismic upgrade [3-6].

FRP reinforcements exhibit linearly elastic behaviour prior to failure and fails in a brittle manner. The weak point in mechanical behaviour of FRP reinforcements is their characteristics in a transverse direction, which can be seen in shear resistance testing, when the strength characteristics of tested samples are significantly reduced. However, FRP reinforcement has several advantages, such as high tensile strength, higher ductility, high corrosion resistance and easy application [7].

Due to an increased demand on FRP for construction industries, determining of the mechanical properties and defining of specific testing procedures are the most important issues for ensuring the reliability of the material. Tensile strength testing is assumed to be the most common method for defining mechanical properties of FRP bars. However, tensile testing is more time-consuming due to the longer time of samples preparation then other types of testing, as the samples should be mounted into grip anchorages from both ends. Therefore, the shear strengthening can be made instead, which does not require a specific samples preparation. Many researchers globally have experimented and studied the shear strength behavior of FRP bars.

Khalifa et al. [8], Täljsten [9], and Triantafillou [10] developed a theory that aims at describing FRP stress distribution along a shear crack with equations of closed-form, as opposed to the regression-based formula as Triantafillou et al. [11] introduced. Finding of the FRP contribution to the resisting shear and the FRP resultant across the crack can be computed when this formula is correctly defined. Strain rate dependency of the shear behavior and the shear modulus of the carbon-epoxy material system IM7-8552 were determined by Koerber et al. [12]. Specifically, when the loading case varied to dynamic from quasi-static, the yield strength, in-plane shear modulus of elasticity and pure failure strength increased by 88%, 25% and 42%, respectively.

The study of the nonlinear behavior of unidirectional Carbon Fiber-Reinforced Polyetheretherketone PEEK in shear and transverse compression was done by Vogler et al. [13]. A biaxial loading fixture was created to perform biaxial tests under three loading history regimes: Transverse compression in the presence of shear stresses (constant), where the shear response under the presence of the transverse compression and proportional loading of transverse shear and compression. It was observed that the increase of the in-plane and transverse shear strength was similar to the increase of the neat resin strength.

High strain rate tests were performed by Hsiao et al. [14] on a split-Hopkinson pressure bar and drop tower. The results were reported for shear strength and modulus, compression strength, modulus and ultimate strain. The findings of the test were that it is not possible to monitor the failure process and the use of the recovery split-Hopkinson pressure bar, created by Nemat-Nasser et al. [15], as suggested.

Gulino at al. [16] studied the relative positions of the yield fronts and deboned fronts depend, among others, on matrix strain-hardening profiles. The results were that beyond the plastic zone, the interfacial shear stress typically decays quite quickly, and the matrix behavior is elastic, thus the shielded zone, and especially the profile of shear stress on the fibre surface is rather complicated. However, an assumption of a constant interfacial shear stress in the exclusion zone has proved to be a useful approximation in which it serves as a useful engineering measure especially in comparing interface treatments and matrix materials.

The low usage of Basalt FRP (BFRP) in the construction industry in the past decades led to a limited amount of studies held on the shear behavior of BFRP. However, Benmokrane et al. [17] proved that the type of the resin plays significant role in the inter-laminar shear strength of BFRP bars, as BFRP bars with epoxy resin showed higher durability than BFRP bars with vinylester resin as well as the durability of GFRP bars was lower than for BFRP bars with epoxy resin.

Wu et al. [18] discovered that the nine weeks of exposing BFRP bars to alkaline solution at 55°C, the loss in shear strength was only limited to around 15%. A report was made by Elgabbas et al. [19] about the degradation of BFRP bar in alkaline solution at 60 °C to be confined to the fibre-resin interface rather than in fibre or resin itself.

Alam et al. [20] studied the shear strength of FRP reinforced members without transverse reinforcement, the authors found that the normalized shear strength increases linearly with the cubic root of the axial stiffness of the reinforcing bars. However, the result shear strength of FRP reinforced elements is proportional to the axial stiffness of the longitudinal reinforcement was studied by Alam et al. [20], El-Sayed et al. [21, 22], and Razaqpur et al. [23]. Hence, the conclusion that the shear strength was proportional to the amount of longitudinal reinforcement was done by Alkhrdaji et al. [24], and the effect of the reinforcement stiffness and amount on the shear strength of FRP elements, despite no significant influence of the longitudinal reinforcement ratio on the shear strength was observed by Yost et al. [25].

2. Experimental programme

2.1. Materials utilized in the work

The shear strength testing was carried out for BFRP, Hybrid FRP (HFRP), and nano-Hybrid FRP (nHFRP) bars with diameters Ø4, Ø6, Ø8, Ø10, Ø12¸ Ø14, and Ø18 mm. The term "Hybridization" in context of this work must be understood as physical substitution of different constituents in order to obtain materials with better and adjustable properties [26].

Different constituents and their volume fraction and location were estimated. Hybridization of carbon and basalt fibres was assumed as the most optimal due to similar strain characteristics of Carbon Low Strength (LS) type of fibres and basalt fibres. Basalt fibres are characterized by weak anisotropy and are not as rigid as carbon fibres. However, basalt fibres were chosen for its environmentally friendly producing process and it is significantly less brittle when used in composites [24]. The HFRP bars (fibres basalt/carbon volume fraction 1:4) were characterised by better mechanical properties in comparison with BFRP as well as better cost-efficiency comparing to Carbon FRP (CFRP) bars [26-29]. The typical properties of constituents of HFRP bars utilized for the work are presented in the Table 1.

Table 1. Typical properties of constituents utilized for preparing HFRP rebars [25]

Properties	Units	Carbon fibres LS	Basalt fibres	Epoxy resin
Density	g/cm^3	1.9-2.1	2.6-2.8	1.2
Diameter	µm	7.0-11.0	11.2-13.4	-
E_{11}	GPa	232.0	89.0	3.5
E_{22}	GPa	15.0	89.0	3.5
v_{12}	-	0.28	0.26	0.35
v_{23}	-	0.49	0.26	0.35
G_{12}	GPa	24.0	21.7	1.3
G_{23}	GPa	5.0	21.7	1.3
σ_{11}	MPa	2500-3500	1153-2100	55-130

E_{ii} is the Young's modulus along axis i, v_{ij} is the Poisson ratio that corresponds to a contraction in direction j when an extension is applied in direction i, and G_{ij} is the shear modulus in direction j on the plane whose normal is in direction i and σ_{ii} is the tensile strength in the direction i [26].

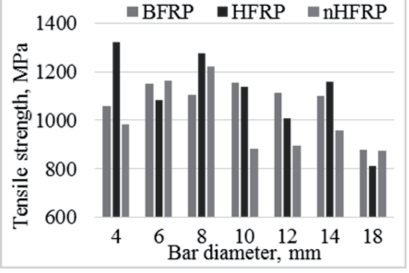
nHFRP bars are modified HFRP bars in which the composition of the matrix has been changed by adding sol with nanosilica particles at a concentration of 25-30% by weight to the epoxy resin. Nanosilica additives were added to resin consistency in order to improve overall properties of the bars, including cohesion and thermal mechanical properties (as it is suggested in sources [30-32]).

Before the production of HFRP and nHFRP bars, some analytical and numerical estimations were made. Overall mechanical properties of composite materials can be calculated by using Voigt Model for the longitudinal direction and Halpin-Tsai Model or other semi-empirical Models for transverse direction.

However, mentioned models do not consider the location of fibres in hybrid bars. Therefore, the numerical analysis was performed in ANSYS® software [33]. Two different bar configurations with carbon fibres in the core region and in the near-surface region were proposed. It was discovered that the location of fibres does not play so important role as their fractions. The difference between various bar configurations can be a maximum of 2%, meanwhile, the volume fraction of all analyzed configurations can influence the final stiffness by 74.6%.

In the next stage, external manufacturing company attempted to produce both configurations. However, while placing carbon fibres in the near-surface region, local scorching was observed, and consequently it was agreed that the carbon fibres should be placed in the core region of the bar.

More detailed description of analytical considerations, numerical simulations and experimental testing of HFRP and nHFRP bars can be found in these companion papers [34-36]. Comparison between mechanical properties of the bars of different types with different diameters obtained in the tensile testing are presented in the Fig 1.



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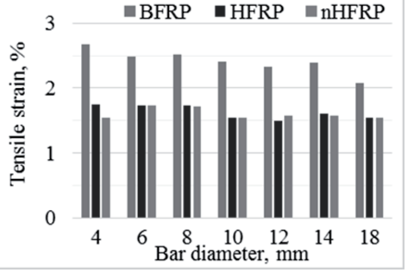

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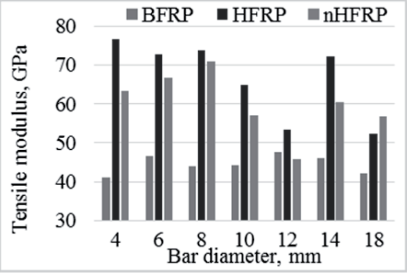


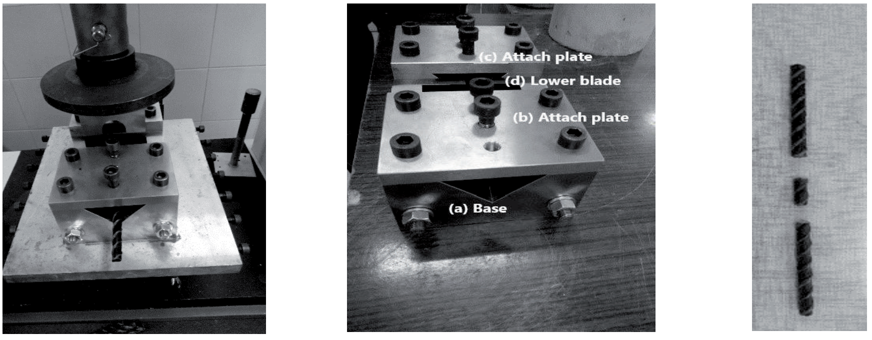
(c)

Fig. 1. Tensile properties of FRP bars with different diameters: (a) Tensile strength, (b) Ultimate tensile strain, (c) Tensile modulus of elasticity

2.2. Test procedure

The shear strength test of FRP bars was carried out in accordance with the methodology described in ACI 440.3R-04 and ASTM D7617 / D7617M – 11 [37].

For the shear strength test, in order to the bar sample to shear in two planes simultaneously, a steel device was constructed with blades converging along a surface perpendicular to the sample axis. The device consists of one upper blade, two lower blades and a sample holder. The sample holder has a V-shaped groove for placing FRP samples and a rectangular notch for holding the lower and upper blades in the center of the upper part of the device. The sample holder has a 100 mm width, 110 mm height, and 230 mm length. It is attached to the instrument stand with screws that stabilize it in order to eliminate the horizontal movement of the bar. In total, the shear test was carried out on 105 bars, 5 bars per each diameter. Fig. 2 shows the testing device and shows the destructed bar due to shearing.



(a) (b) (c)

Fig. 2. Double shear test: (a) Instron 3382 Universal Test Machine stand, (b) Double shear testing device, (c) Shear failure of the FRP bar

During the shear strength testing, all the FRP bars were tested to obtain the maximum shear force; all the FRP bars were tested at speed up to 50 MPa / min, due to the high sensitivity of shear results since loading time, for 3.5 to 4.5 minutes.

According to ACI 440.6-08 and ASTM A615 / A615M [37] methodologies, shear strength, f_s, was calculated according to the Eq. 1 using an equivalent cross-sectional diameter of the bars (equivalent cross-sectional diameter is measured according to test procedure B1 ACI 440.3R).

$$f_s = F_u / 2A \quad (1)$$

Where:

F_u – The maximum shear force;

A – The equivalent cross-sectional diameter of the tested bar

2.3. Results and discussion

During the shear testing, it was observed that the destruction of the bars can occur in two different ways, when shearing occurs in one and then slightly later in the other cross-section of the tested bar is described by the "R" line (dotted line). In contrast, the "B" line is typical for simultaneous shearing of a bar in two planes, displayed in the Fig. 3.

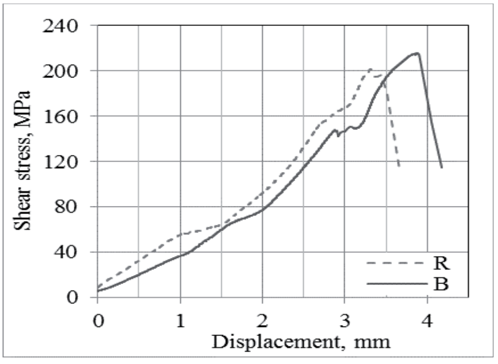
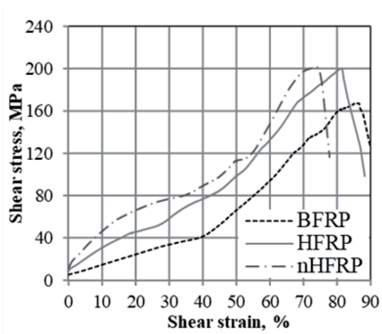


Fig. 3. Shear stress-displacement graph for two different failure modes of HFRP bars with diameter of 14mm.

Both of the destruction modes can be acceptable, in most of the cases the destruction was caused by simultaneous shear of the bar in two vertical planes. However, the case "R" can be interpreted as a beginning of the case “B”, because in a few seconds the other cross-section fails by another vertical plane. This tendency was observed for several bars with different diameters, when the bars are failing due to one plane then the maximum shear strength obtained is approximately 10 lower then for simultaneous shear failure in both of the sections (Fig. 4). The measurements of the strains were made on the basis of the outcomes from UTM (Universal Testing Machine).



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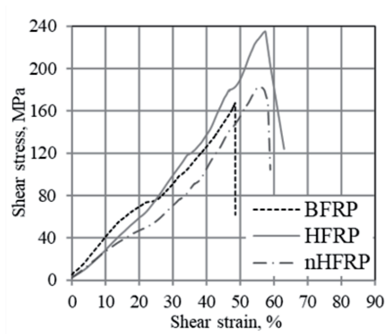

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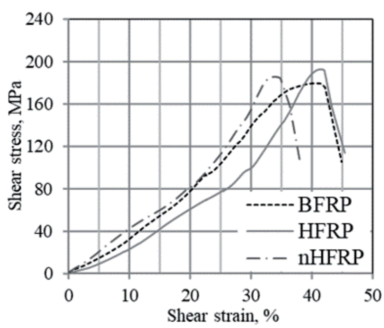

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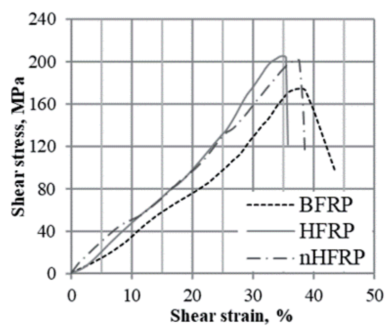

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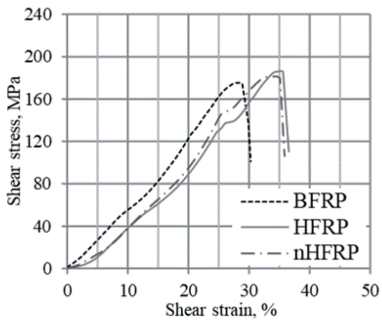


(e)

Figure 4. Shear stress-strain relation for FRP bars with different diameters: (a) 4mm, (b) 8mm, (c) 12mm, (d) 14mm, (e) 18mm

Basing on the results due to the non-uniform slope of the shear curves it is impossible to determine the correlation between results (as it can be seen in tensile testing). Therefore, some other parameters should be specified for predicting shear strength for another types of FRP bars and diameters. Comparing BFRP bars to HFRP and nHFRP bars, it can be seen that BFRP bars have greater shear deformation and less shear strength compared to HFRP and nHFRP bars. Table 2 describes shear strength testing results depending on different diameters and types.

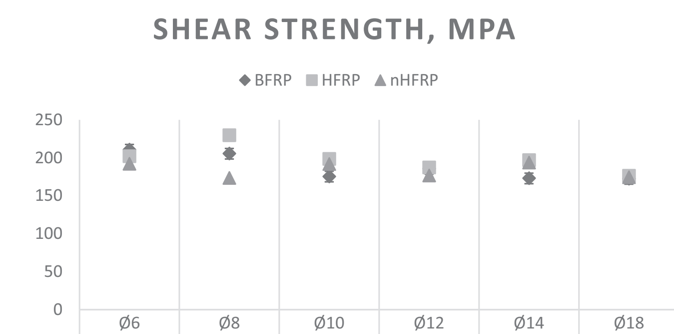
Table 2. Shear strength testing results of FRP bars for different diameters

Bar	Parameter	Unit	Ø4	Ø6	Ø8	Ø10	Ø12	Ø14	Ø18
BFRP	f_s	MPa	171.33	210.66	205.37	175.33	185.46	172.85	172.25
	SD	MPa	7.15	3.84	11.57	6.46	4.70	8.59	6.90
	COV	%	4.17	1.82	5.63	3.68	2.54	4.97	4.01
HFRP	f_s	MPa	204.41	202.04	229.44	198.31	187.09	196.84	176.35
	SD	MPa	5.87	17.51	4.06	6.17	5.99	12.06	9.75
	COV	%	2.87	8.67	1.77	3.11	3.20	6.13	5.53
nHFRP	f_s	MPa	193.25	192.08	173.48	191.64	176.64	193.66	174.37
	SD	MPa	12.34	4.40	6.54	5.49	5.42	9.46	9.17
	COV	%	6.39	2.29	3.77	2.86	3.07	4.88	5.26

SD – Standard Deviation; COV – Coefficient of Variations

It is worth mentioning that the type of FRP bars affects the COV differentiation for shear strength. Significant scatter of shear testing results can be explained by heterogeneous nature of FRP material. HFRP and nHFRP bars are characterized by 20% higher average values of lateral shear strength compared to BFRP bars that amounts to 170 till 210 MPa.

The transverse shear strength displays a slight downward trend as the bar diameter increase, which is the most noticeable for HFRP bars. However, a little variation is observed in the shear strength data, with COV greater than in the rebar tension tests. Fig. 5 shows the comparison of shear strength results for different diameters.



	Ø6	Ø8	Ø10	Ø12	Ø14	Ø18
◆ BFRP	210,66	205,37	175,33	185,46	172,85	172,25
■ HFRP	202,04	229,44	198,31	187,09	196,84	176,35
▲ nHFRP	192,08	173,48	191,64	176,64	193,66	174,37

Fig. 5. Shear strength comparison for different bars diameters and types

Comparing the average shear strength of BFRP bars to HFRP bars, the average shear strength values of BFRP bars were lower than the average shear strength values of HFRP bars for all diameters except for diameter 6mm, where it is slightly higher, by approx. 1%. The bar diameters given in the results are nominal. For HFRP bars with a nominal diameter of 6 mm, their equivalent diameter was greater than the equivalent diameter of BFRP bars of the same nominal diameter. At the same time, the volume fraction of fibres in both types of bars was similar. Therefore, the tensile and shear strength of the HFRP bars was slightly lower than that of BFRP bars of the same nominal diameter. However, for other diameters the average shear strength of BFRP bars was lower; shear strength for Ø4, Ø8, Ø10, and Ø14 was lower by approximately 20% and for Ø12 and Ø18 the difference of results was not significant. In bars with a nominal diameter of 12 mm, the volume fraction of fibres for HFRP was lower compared to BFRP bars, which resulted in a slight difference in shear strength.

On the other hand, for bars with a nominal diameter of 18 mm, the share of the fibre volume fraction in the HFRP bars was 20% lower than in the BFRP bars with a similar equivalent diameter, which resulted in similar shear strength of both types of reinforcement.

Considering the average shear strength of BFRP bars and nHFRP bars, for BFRP bars with Ø4, Ø10, Ø14, and Ø18 the values were also lower than results obtained for nHFRP bars with the same diameters. The average shear strength of BFRP bars with Ø4, Ø10, and Ø14 was lower than the average shear strength of nHFRP with the same diameter by approximately 13%, for BFRP bars with Ø18 the outcomes were slightly lower, by approximately 1%. However, for BFRP bars with the diameters Ø6, Ø8, and Ø12, the shear strength was slightly higher compared to the corresponding nHFRP bars. In this case, in nHFRP bars with the same nominal diameters as the BFRP bars, the equivalent diameters of the HFRP reinforcement were greater than the equivalent diameters of the BFRP reinforcement, which explains the obtained shear strength values.

3. Conclusions

Current testing on different types of FRP bars allows for better understanding of the mechanical behaviour of those bars. Shear testing is needed to estimate shear strength of the bars, which is the maximum stress that the specimen can hold before failure of the specimen occurs.

In accordance with shear strength-strain relationship, the higher results were recorded for HFRP bars. In most of the cases the results were higher by approx. 20% comparing to non-hybrid, BFRP bars, which can explain the sense of such physical substitution of fibres. Only for bars with a nominal diameter of 6 mm higher shear strength was noted for BFRP bars, which was caused by the difference in the equivalent diameter between BFRP and HFRP bars

However, comparing obtained results for HFRP and nHFRP bars, shear strength of nHFRP bars was always lower. This may happen due to incorrect redistribution of nano-silica particles in the resin. Considering the mechanical properties obtained from tensile testing of these bars [34], nHFRP bars were having higher results, which may indicate better redistribution for the bars with bigger diameters. Further analyses are required in order to determine the optimal procedure of distribution of nano additives in the bars and obtain FRP bars with better and adjustable properties.

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References

[1] A. Ghobarah, T. El-Amoury, "Seismic rehabilitation of deficient exterior concrete frame joints", Journal of Composites for Construction 9 (5): 408-416, 2005. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:5(408)

[2] S. Durgadevi, S. Karthikeyan, N. Lavanya, & C. Kavitha, "A review on retrofitting of reinforced concrete elements using FRP", Materials Today: Proceedings 26: 3595-3599, 2020. https://doi.org/10.1016/j.matpr.2020.03.148

[3] A. Nanni, A. De Luca, H. Jawaheri Zadeh, "Reinforced concrete with FRP bars: Mechanics and design", CRC Press, Boca Raton, FL, 182-188, 2014.

[4] P. L. Narloch, M. Lidner, E. Kunicka, M. Bielecki, "Flexural tensile strength of construction elements made out of cement stabilized rammed earth", Procedia Engineering, vol. 111, pp. 589-595, 2015. https://doi.org/10.1016/j.proeng.2015.07.049

[5] K. Protchenko, M. Włodarczyk, and E. D. Szmigiera, "Investigation of Behavior of Reinforced Concrete Elements Strengthened with FRP," Procedia Engineering, vol. 111, pp. 679–686, 2015. http://doi.org/10.1016/j.proeng.2015.07.132

[6] P. Woyciechowski, P.L. Narloch, D. Cichocki, "Shrinkage characteristics of cement stabilized rammed earth", MATEC Web of Conferences, vol. 117, no. 00178, 2017. https://doi.org/10.1051/matecconf/201711700178

[7] E. D. Szmigiera, M. Urbański, and K. Protchenko, "Strength Performance of Concrete Beams Reinforced with BFRP Bars," in International Congress on Polymers in Concrete (ICPIC 2018) : Polymers for Resilient and Sustainable Concrete Infrastructure, pp. 667–674, 2018. http://doi.org/10.1007/978-3-319-78175-4_85

[8] A. Khalifa, W. J. Gold, A. Nanni, and A. M. I. Aziz, "Contribution of externally bonded FRP to shear capacity of RC flexural members", ASCE Journal of Composites for Construction, 2(4): 195-202, 1998.

[9] B. Täljsten, "Strengthening of concrete structures for shear with bonded CFRP-fabrics", Recent advances in bridge engineering, Advanced rehabilitation, durable materials, non-destructive evaluation and management, Eds. U. Meier and R. Betti, Dübendorf, 57-64, 1997.

[10] T. C. Triantafillou, "Shear strengthening of reinforced concrete beams using epoxy bonded FRP composites", ACI Structural Journal, 95(2), March-April, 107-115, 1998.

[11] T. C. Triantafillou, and C. P. Antonopoulos, "Design of concrete flexural members strengthened in shear with FRP", ASCE Journal of Composites for Construction, 4(4), 198-205, 2000.

[12] H. Koerber, J. Xavier, P.P. Camanho, "High strain rate characterization of unidirectional carbon-epoxy im7-8552 in transverse compression and in-plane shear using digital image correlation", Mechanic Material 2010, 42, 1004–1019, 2010.

[13] T.J. Vogler, S. Kyriakides, "Inelastic behavior of an AS4/PEEK composite under combined transverse compression and shear", Part I: Exp. International Journal Plastics 15, 783–806, 1999.

[14] H.M. Hsiao, I.M. Daniel, R.D. Cordes, "Strain rate effects on the transverse compressive and shear behavior of unidirectional composites", Journal Composite Material 33 (17), 1620–1642, 1999.

[15] S. Nemat-Nasser, J.B. Isaacs, J.E. Starret, "Hopkinson techniques for dynamic recovery experiments", Proceeding of the Royal Society of London, Series A. 435, 371–391, 1991.

[16] R. Gulino, P. Schwartz, and S. L. Phoenix, "Experiments on shear deformation, debonding and local load transfer in a model graphite/glass/epoxy micro-composite", Journal Materials Science, 26, 6655-6672, 1991.

[17] B. Benmokrane, F. Elgabbas, E.A. Ahmed, P. Cousin, "Characterization and comparative durability study of glass/vinylester, basalt/vinylester, and basalt/epoxy FRP bars", Journal of Composites for Construction 19 (6) 04015008, 2015. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000564

[18] G. Wu, X. Wang, Z.S. Wu, Z.Q. Dong, Q. Xie, Degradation of basalt FRP bars in alkaline environment, Science Engineering Composite Materials 22 (6) (2015) 649–657, 2015. http://dx.doi.org/10.1515/secm-2014-0040

[19] F. Elgabbas, E.A. Ahmed, B. Benmokrane, "Physical and mechanical characteristics of new basalt-FRP bars for reinforcing concrete structures", Construction Building Materials 95 623–635, 2015. http://dx.doi.org/10.1016/j.conbuildmat.2015.07.036

[20] MS. Alam, A. Hussein, "Experimental investigation on the effect of longitudinal reinforcement on shear strength of fibre reinforcement on shear strength of fibre reinforced polymer reinforced concrete beams", Can Journal Civil Engineering 38:243–51, 2011.

[21] AK. El-sayed, EF. El-Salakawy, B. Benmokrane, "Shear strength of FRP-reinforced concrete beams without transverse reinforcement" ACI Structural Journal 103(2):235–43, 2006.

[22] A. K. El-sayed, E. F. El-Salakawy, B. Benmokrane, "Shear capacity of high-strength concrete beams reinforced with FRP bars", ACI Structural Journal 103(3):383–9, 2006.

[23] A. G. Razaqpur, B. O. Isgor, S. Greenaway, A. Selley, "Concrete contribution to the shear resistance of fibre reinforced polymer reinforced concrete members", Journal of Composite for Construction 8(5):452–60, 2004.

[24] T. Alkhrdaji, M. Wideman, A. Belarbi, A. Nanni, "Shear strength of RC beams and slabs", In: Figueiras J, Juvandes L, Faria R, editors. Composites in construction. Lisse, The Netherlands: A.A. Balkema Publishers; p. 409–14, 2001.
[25] JR. Yost, SP. Gross, DW. Dinehart, "Shear strength of normal strength concrete beams reinforced with deformed GFRP bars", Journal of Composite for Construction 5(4):263–75, 2001.
[26] A. Garbacz, E.D. Szmigiera, K. Protchenko, M. Urbański, "On Mechanical Characteristics of HFRP Bars with Various Types of Hybridization", In M. M. Reda Taha, U. Girum, & G. Moneeb, M. M. Reda Taha, U. Girum, & G. Moneeb (Eds.), International Congress on Polymers in Concrete (ICPIC 2018) : Polymers for Resilient and Sustainable Concrete Infrastructure. Washington: Springer, 653–658, 2018. http://doi.org/10.1007/978-3-319-78175-4_83
[27] K. Protchenko, K. Młodzik, M. Urbański, E. Szmigiera, & A. Garbacz, „Numerical estimation of concrete beams reinforced with FRP bars", In MATEC web of conferences (Vol.86, p. 02011). EDP Sciences. Moscow, Russia. 2016.
[28] K. Protchenko, J. Dobosz, M. Urbański, A. Garbacz, "Wpływ substytucji włókien bazaltowych przez włókna węglowe na właściwości mechaniczne prętów B/CFRP (HFRP)" [EN: Influence of the substitution of basalt fibres by carbon fibres on the mechanical behavior of B/CFRP (HFRP) bars]. Czasopismo Inżynierii Lądowej, Środowiska i Architektury, JCEEA 63, 1/1:149–156, 2016.
[29] K. Protchenko and E. D. Szmigiera, "Post-Fire Characteristics of Concrete Beams Reinforced with Hybrid FRP Bars," Materials, vol. 13, no. 5, pp. 1–15, 2020.
[30] J.W. Baur, C. Chen, R.S. Justice, D.W. Schaefer, "Highly dispersed nanosilica-epoxy resins with enhanced mechanical properties", Polymer Vol. 49, pp. 3805–3815, 2008. https://doi.org/10.1016/j.polymer.2008.06.023
[31] Jesionowski, T.; Pilawka, R. Kompozycje epoksydowe z krzemionką [Epoxy composites with silica] Kompozyty 2009, Vol. 9, No. 2, pp. 112-116.
[32] T. Jesionowski, R. Pilawka, „Kompozyty epoksydowe z krzemionką sieciowane 1-etylomimidazolem [Epoxy composites with silica crosslinked with 1-ethylimidazole]", Kompozyty Vol. 11 No. 1: 14-17, 2011.
[33] ANSYS® Academic Research Mechanical, Release 16.2, Help System, Coupled Field Analysis Guide; ANSYS, Inc.: Canonsburg, PA, USA, 2016.
[34] K. Protchenko, E.D. Szmigiera, M. Urbański, A. Garbacz, "Development of Innovative HFRP Bars", MATEC Web of Conferences 196: 1–6, 2018. http://doi.org/10.1051/matecconf/201819604087
[35] E.D. Szmigiera, K. Protchenko, M. Urbański, A. Garbacz, "Mechanical Properties of Hybrid FRP Bars and Nano-Hybrid FRP Bars", Archives of Civil Engineering 65(1): 97–110, 2019. http://doi.org/10.2478/ace-2019-0007
[36] K. Protchenko, F. Zayoud, E.D. Szmigiera, M. Urbański, „Tensile and Shear Testing of Basalt Fiber Reinforced Polymer (BFRP) and Hybrid Basalt/Carbon Fiber Reinforced Polymer (HFRP) Bars", Materials, 2020, 13(24), 5839. https://doi.org/10.3390/ma13245839
[37] American Concrete Institute (ACI). Guide test methods for fibre reinforced polymers (FRPs) for reinforcing or strengthening concrete structures. ACI: Farmington Hills, USA, 2006; ISBN 9780870317811.

Badanie wytrzymałości na ścinanie prętów BFRP, HFRP oraz nHFRP

Słowa kluczowe: Hybrydowe zbrojenie FRP, Zbrojenie na bazie Fibre-Reinforced Polymers (FRP), Pręty nHFRP, badania wytrzymałości na ścinanie, pręty kompozytowe

Streszczenie:

W ostatnich dziesięcioleciach coraz większą rolę odgrywa zastosowanie zrównoważonych materiałów w budownictwie. Dlatego pręty kompozytowe Fibre-Reinforced Polymers (FRP) zwróciły uwagę inżynierów budownictwa ze względu na szereg zalet takich jak: zwiększoną trwałość, pełny recykling, odporność na korozję, mały ciężar i wysoką wytrzymałość. W artykule opisano wyniki badań wytrzymałości na ścinanie trzech typów prętów kompozytowych: (i) złożonych z włókien bazaltowych (BFRP) i matrycy epoksydowej, (ii) hybrydowych – wykonanych z włókien bazaltowych z dodatkiem włókien węglowych oraz matrycy epoksydowej (HFRP) a także (iii) nano-hybrydowych (nHFRP), złożonych z włókien bazaltowych i węglowych z udziałem zmodyfikowanej matrycy epoksydowej z dodatkiem nanokrzemionki. Pręty HFRP i nHFRP są znacznie tańsze niż pręty wykonane wyłącznie z włókien węglowych Carbon FRP (CFRP) a jednocześnie znacznie bardziej sztywne w porównaniu do prętów wykonanych wyłącznie z włókien bazaltowych FRP (BFRP). Pręty BFRP, HFRP i nHFRP o średnicach w 6,

8 , 10 ,12, 14, 18 mm poddano badaniom wytrzymałości na ścinanie w celu określenia właściwości mechanicznych oraz mechanizmu zniszczenia. Uzyskane wyniki wykazują niewielką tendencję spadkową wytrzymałości na ścinanie wraz ze wzrostem średnicy pręta, co jest najbardziej zauważalne w przypadku prętów HFRP. W większości przypadków pręty BFRP charakteryzowały się większym odkształceniem na ścinanie i mniejszą wytrzymałością na ścinanie w porównaniu z prętami z HFRP i nHFRP. Przeprowadzone testy mogą przyczynić się do pełnego zrozumienia mechanicznego zachowania się tych typów prętów FRP.

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