EFFECTIVENESS OF FLEXURAL BASALT REINFORCEMENT APPLICATION IN RC BEAM STRUCTURES

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Summary:
Basalt bars for concrete reinforcement called Basalt Fiber Reinforced Plastic (BFRP) is a new material, so it is necessary to identify the differences and limitations of their use in relation to traditional steel reinforcement. The paper presents some chosen results of research on the flexural behavior of model beams reinforced with BFRP bars, compared to the reference beams with steel reinforcement. The tested beams were made of C30/37 concrete and flexural reinforcement of basalt bars with 8 mm diameter. The tensile test of BFRP bars has been conducted and the analyses of the beam deformability and flexural capacity have been performed. The results show the different character of the load-deflection dependence of basalt reinforced beams compared to traditionally reinforced beams, as well as the significant influence of the type and quality of anchoring on the basalt bars crack process.

Keywords: basalt rebar, BFRP, flexural capacity, reinforced concrete, deflections.

Introduction

Basalt fiber reinforced plastic (BFRP) is a quite new type of concrete reinforcing rebar that are stronger than conventional steel bars and at the same time are completely resistant to corrosion.

The current cost of repair and maintenance of infrastructure around the world is estimated to exceed more than 100 trillion euro's (fib Bulletin 40/2007). A large part of the costs is associated with providing durability of concrete structures. According to a study conducted by CC Technologies for the Federal Highway Administration (G. Koch et al. 2002) alone the costs of corrosion attack in road and bridge RC construction industry the U.S.A. government agencies estimate at $ 276 billion / year (about 3.1% of GDP). For example, in the period from 1987 to 1993 200 000 tonnes of steel bars epoxy-coated plates were used in the bridge, but a significant percentage of them is degraded (Hollaway 1993).

In today's world there is a wide range of available technologies delaying corrosion of reinforcement for concrete. Each of them has its own particular advantages and economics. The following types of protection against corrosion of reinforcement used in concrete structures could be specified:

- protective coatings and linings,
- metal coatings and linings,
- corrosion resistant alloys,
- corrosion inhibitors,

- cathodic and anodic protection
- corrosion resistant composites

Several enhancements methods (such as galvanizing and coating of steel rebar), as well as alternative reinforcement (such as carbon fiber reinforcement (CFRP) or glass fiber reinforcement (GFRP) were tested in the past. The recent introduction of composite basalt as reinforcing bars shows many advantages in comparison with conventional steel bars.

Basalt FRP bars are an excellent alternative as bridge girder spans due to minimizing the weight of the slab, reducing repairs and a significant increase in usability (Karbhari 2007).

Service life of concrete slabs with conventional steel reinforcement for the use in bridges, is estimated for 25 years. From the other hand the life of panels with FRP reinforcement is usually expected to be at least 75 years (i.e. the period of use of the bridge) (Hooks, O'Connor 2004). The study showed that after two years in tropical conditions and in highly alkaline environment physico - chemical properties of FRP reinforced platforms have not been degraded (Tomosawa, Nakatsuji 1997), (Clarke, Sheard 1998). Also, an inspection made at 20 and 25 years of use in Mondial House Building (built in 1974) has shown that the design of FRP reinforced plate elements is almost as good as new (Karbhari 2007).

In May 2008, Southeast University, Zhejiang GBF Basalt Fiber Co., Ltd. and Zhang Shi Shijiazhuang – both highway managing companies - developed a technology of continuous reinforcing process of building structures, using BFRP reinforcement to strengthen the road at the north and south ends of the Xingtang crossing bridge. The technology of constructing a continuous reinforcement eliminated the need for welded joints, thereby reducing shrinkage cracks of concrete blocks, but also solved the problem of corrosion of steel reinforcement effect due to de-icing salt, thereby positively affecting the quality and durability of highways and motorways and has reduced costs and shortened construction time (Wu Z. *et al*. 2012).

The problem of determining the real stress – strain relationship of reinforcement rebar made of composite-based materials, such as glass, aramid (Kevlar), or carbon fibers exists for the last two decades.

For example, in the SLS design the use of indirect methods for determining the width of the cracks on the bars distance basis, as a function of the tension in the reinforcement, and concrete cover is not recommended for the FRP bars.

For the service load the maximum width of the cracks may be assumed greater than that for conventional reinforced concrete, due to high BFRP resistance to corrosion. The recommended crack width limit values for FRP reinforced elements recommended by Canadian Standards (CSA 2002) are:

- for external reinforcement 0.5 mm (0.3 mm for steel),
- for internal reinforcement 0.7 mm (0.4 mm for steel).

Together with the implementation of FRP materials in the engineering structures it became necessary to determine their mechanical parameters. Due to the anisotropic structure of composite materials and isotopic steel reinforcement, the modified stress-strain relationships have to be considered.

Characteristics of basalt reinforcement (basalt fibers and basalt bars)

Basalt

Basaltic rock is one of the most common mineral in the world. Basalt is a fine-grained, volcanic rock with a dark color (green or black), which often glassy appearance, consisting mainly of three minerals, it is of plagioclase, pyroxene and olivine. Basalt rock is effusive fine and has a higher content of iron and magnesium than granite. Most of basalt, which can be found on Earth arose in just three types of rock formations:

1) oceanic rift zones,
2) hot spots oceanic,
3) mantle plumes and continental hot spots.

Basalt has good thermal properties, strength and durability. The density of basalt rock ranges from 2.8 to 2.9 g/cm³. Basalt is a very hard rock with Mosh hardness of 5 to 9. Crushed basalt is commonly used for road foundations, as aggregate for concrete, aggregate for asphalt, aggregate railway and coal as a filter for surface drainage.

Basalt fibers

Basalt reinforcing rods are made of very thin basalt fibers which are similar to the carbon and glass fibers, but have better physical and mechanical properties than glass fibers, and are significantly less expensive than carbon fibers.

In the first stage of production basalt crushed volcanic rock is melted at a temperature of from about 1400 to 1700 °C. The molten rock is then extruded through special platinum nozzles for the production of continuous basalt fiber strands. The fibers due to their shape of a hexagonal chains are much more durable than steel or glass fibers (Van de Velde et al. 2002). As a result of the production of fibers there are no wastes in the environment. The fibers are non-toxic in use, and to recycle. Typically, basalt fibers consist of strands with the thickness 6, 9 and 13 micrometers. Initially, after World War II (in the former Soviet Union, the U.S.A. and Europe) basalt fibers used in military and aerospace industries. The first industrial production of continuous basalt fiber (BCF) was launched in Kiev, Ukraine in 1985. Many countries within the European Union, Japan, South Korea and China are working on basalt fiber technology. The current annual production of basalt fiber BCF is approximately 3000 - 5000 tonnes (Basaltex 2008).

BFRP basalt bars

Composite basalt rebars - Basalt Fiber Reinforced Plastic (BFRP) are made of continuous basalt fiber, epoxy and polyester using pultrusion process. 80% by weight of fibers made of basalt rock and 20% filler in the form of an epoxy resin, and winding improving the adhesion properties (Bank 2006). Often resin matrix for basalt fiber is used as a polymeric vinyl ester. Vinyl ester resin is a combination of epoxy resin and unsaturated polyester resin (Karbhari 2007). The advantage of vinyl ester resins is that they have similar physical properties of the epoxy resins and preferred characteristics required for the processing of the polyester resin. Structural composites may be defined as a system of heterogeneous material consisting of two or more components on a macroscopic scale, which in combination, can provide new improved properties that are superior to the properties of the components. Thus, fiber reinforced polymer composite consists of fibers of high strength and rigidity of the polymer matrix embedded with a relatively lower strength and stiffness.

Generally, the fiber is the main support element and the polymer matrix is designed to provide the desired direction of the composite to facilitate the transfer of the load on the fiber and to protect the fiber from environmental factors associated with elevated temperature and ambient humidity (Hollaway 1993).

In contrast to steel, which is an isotropic material, the basalt bars (basalt composite) are anisotropic material, which implies a difference in mechanical properties in the longitudinal and transverse directions. Anisotropy of basalt bars causes that the longitudinal properties are determined by the properties of the fiber, while the transverse and shear properties are governed by the properties of the resin. A mechanism of basalt bars destruction after rupture shown in Figure 1 (Urbański et al 2013).

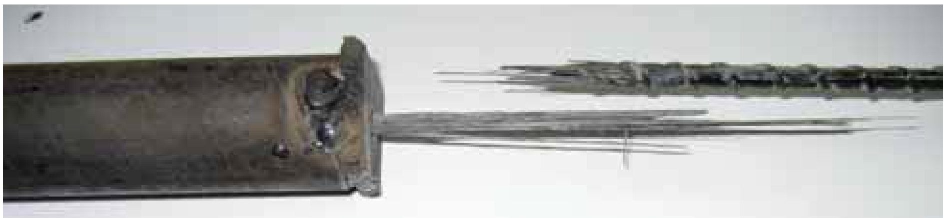

Fig. 1. Failure mode of the rupture of basalt bar (Urbanski et al 2013)

In the table 1 there are presented some chosen comparison of mechanical and physical properties of basalt and steel bars.

Tab. 1. Comparison of basalt and steel rebar (Basaltex 2008, RockBar 2010).

Nr	Characteristics	Steel	BFRP	Comments
1	Density, t/m^3	7,8	1,80	4 times lighter
2	Weight 1m bar in kg Ø10 Ø12	0,617 0,888	0,150 0,221	4 times lighter
3	Ultimate strength, MPa			
	In tension In compression	485 485	1200 420	above 2 times more
4	Young's Modulus, GPa	200	52÷57	
5	Thermal conductivity, kcal/(h m °C)	38	0,35 ÷0,59	66÷111 times less
6	Linear thermal expansion , 10^{-6} m/mK,	12	9 ÷12	similar

7	Length of 1 ton bar, m Ø10 Ø12	 1 621 1 126	 5 848 4 330	4 times larger (transport !)
8	Elongation , %	14,5	2,2÷2,5	6 times less
9	Poisson ratio, ν	0,3	x	

Some significant advantages of reinforcing bars made on the basis of basalt BFRP compared to the conventional steel reinforcement are listed below, as follows.

– Much higher (more than twice) the tensile strength of the reinforcement steel or GFRP glass fiber, at the same diameter (Bank 2012).
– BFRP bars do not corrode and therefore the thickness of the concrete cover may be reduced. This allows the use of thinner concrete sections, resulting in material savings and cost.
– BFRP bars are 89% lighter than steel reinforcing bars; one ton of basalt rebar reinforcement replaces 9.6 tons of reinforcing steel. One person can easily lift 150 m roll of 10 mm BFRP. Thus, there is no need to transfer the BFRP any cranes, forklifts and trucks.
– The low weight of BFRP allows faster construction and installation of reinforcement.
– Very high strength allows to use rebars of a smaller diameter (in many cases, the diameter of the reinforcement can be reduced by applying the BFRP).
– BFRP bars have a similar thermal expansion coefficient as for concrete and steel, therefore the BFRP bars expand and shrink at similar rate compared to the concrete. (Karbhari 2007).
– BFRP bars are inherently resistant to corrosion, rust, alkalis and acids (Bin Wei *et al*. 2010). Basalt rebar is indifferent to the high pH of the concrete. BFRP bars do not rust, so the concrete cracks due to swelling corrosion products are completely eliminated. In contrast to the GFRP bars BFRP bars do not need a special coating to protect against exposure to high pH of concrete.
– Basalt fibers do not absorb and do not send moisture, like glass fibers do (Wu Z. *et al*. 2012). Moreover, the protruding fibers do not form any paths for water, which could penetrate and destroy the concrete.
– BFRP bars do not conduct electricity, which prevents electrolysis in construction exposed to the sea.
– BFRP bars are non-magnetic and they do not induce any magnetic field when exposed to electromagnetic or radio frequency energy (RF). Therefore, they can be used in rooms with magnetic resonance imaging (MRI) and close to radio frequency identification reader (RFID) (Sim *et al*. 2005).
– Basalt fiber can be used in a wide range of temperatures, -260/-200 ° C to about 650/800 ° C, with a melting point of 1450 ° C. Although the content of the resin bars BFRP, limiting temperature range is from - 70 ° C to +100 ° C, and are therefore useful in applications that require resistance to fire. BFRP bars also have low thermal conductivity, are non-flammable and do not emit any harmful

substances in fire (Subramanian *et al*. 1977).

Disadvantages of BFRP bars

- BFRP bars are brittle in nature (do not extend as far as the steel bars before breaking off), so are not suitable for use in areas prone to earthquakes.
- Bending of the cross-sections is unacceptable; BFRP bars are not weldable.
- BFRP bars are designed primarily for reinforcement in tension zone elements.
- Compared to steel bars, BFRP bars have a lower modulus of elasticity, which results in some increase in the deflection elements.
- Cross cutting, cutting bars are not recommended cause rapid dulling and steel shear fracture as a result of crushing steel. Hacksaw or abrasive wheels may be a good alternative. The best choice is cheap, circular saw blade with a diamond inexpensive. Massive cuts may be made cutter or a saw blade, gas, mineral however wet cutting is more favorable.
- Contrary to steel bars, BFRP bars are not ductile and have brittle destruction when the ultimate tensile strength is reached. Therefore, it is important to keep the permanent load below the limit strength of an adequate margin of safety.
- BFRP bars cost may be higher than steel bars. However, the Russian Federation has produced basalt bars relatively cheaper than steel bars.

The study of flexural concrete members reinforced with basalt bars

Research assumptions

Warsaw University of Technology began research on the effectiveness of the application of basalt bars for reinforcement of flexural concrete structures. The primary objective of the study was to identify the main mechanical properties of reinforcing bars made of BFRP basalt fiber, and to determine their suitability as reinforcement for the beams subjected to bending. Determination of mechanical properties of BFRP bars 8 mm in diameter consisted of determining the tensile strength, strains at fracture limit, the average modulus of elasticity, and determining the stress limits of bond between the reinforcing bars and the surrounding concrete.

The research program contained a bending test of three model beams with bottom flexural reinforcement made of 3 BFRP bars with a diameter of 8 mm and 3 reference beams with bottom steel reinforcement. The simply supported beams with a clear span 1000 mm have the cross-section $b \times h$ = 80×140. Top reinforcement in the regions of supports of all tested beams consisted of 2 steel bars with a diameter of 8 mm. The scheme of the tested beam and the location of benchmarks are shown in Figure 2. In all the beams the central bottom bar was protruded on both end sides (as presented in the Fig.2) to enable the measurement of the slip during the loading process.

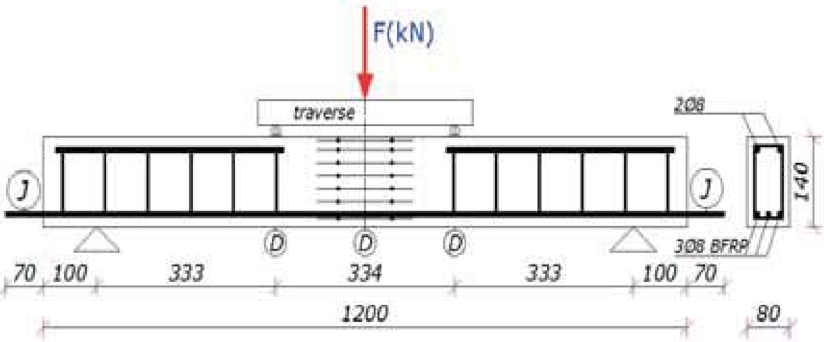

Fig. 2. Scheme of tested beam with bottom reinforcement (BFRP bars) and the location of benchmarks used to measure the concrete strains with an extensometer, J - slip measurement sensor, D - deflection measurement sensor, beam dimensions in mm

Reference beam reinforcement system (only reinforced with steel bars) was identical as in BFRP beams.

The testing procedures

Load was carried by the beam in the four point system made of steel traverse, respectively in the third and two thirds in the beam span.

In the first series the beams were subjected to load up to 10 kN, and then release to 5 kN. In the second cycle load was increased to 20 kN, and then released to 5 kN. In the last third cycle the beams were loaded until failure.

The Figure 3 shows the mode of failure of beam BFRP 3 in the final phase of the load equal to 45 kN. It is noteworthy that there was no rupture of the bottom reinforcement basalt bars. The destruction took place by shear in support zones of the BFRP beams and it had fragile nature. However, there was no sudden destruction due to continuous reinforcement preserved basalt. More detailed description of testing procedures are presented in the paper (Lapko and Urbanski 2013).

Fig. 3. The BFRP beam with flexural basalt reinforcement reaching critical load capacity equal to 45 kN (Lapko and Urbanski 2013)

Results of experimental tests

In the table 2 there are presented chosen results of BFRP beam deflections (vertical displacements in the mid span) with basalt reinforcement and the deflections of reference beams (SRC), depending on the load.

Tab. 2. Deflections of BFRP beams with flexural basalt bars and reference SRC beams with flexural steel reinforcement

Loading force, kN	Mid span beam deflections in mm					
	SRC1	SRC2	SRC3	BFRP1	BFRP2	BFRP3
5	0.97	1.81	1.61	3,21	3.04	3.10
10	1.71	2.23	2.06	4.35	4.11	4.23
20	2.45	3.30	3.14	7.33	6.99	7.21
30	3.48	4.43	4.24	12.63	11.58	12.01
40	x	x	x	-	19.54	19.03

In the case of SRC1 reference beam the measured deflections are different from the other two reference beams due to the different initial cycle of the load - strain.

In BFRP beams with basalt flexural bars, in contrast to the reference SRC beams the deformations of the reinforcement were linear, thus the increase of deflection in relation to the increase of loading force was practically constant, until the destruction of the element. Figure 4 shows for the tested beam BFRP3 and for comparison for the reference beam SRC3 the diagrams of the deflections versus beam loading forces.

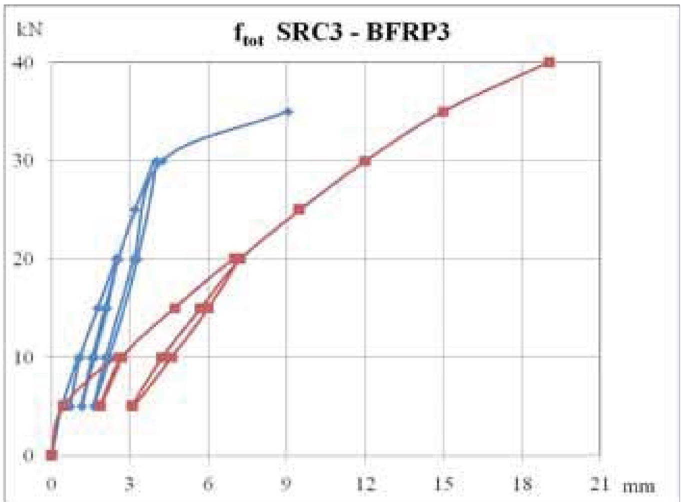

Fig. 4. The relationship: deflections versus loading force of the beam BFRP3 (squares) and the reference beam SRC3 (diamonds)

The increased deflections of beams with basalt reinforcement, compared to the reference beams with steel reinforcement can be clearly seen. The reason for the larger value of deflections of BFRP beams was its lower stiffness in relation to reference conventionally reinforced beams. Deflections in the mid span of beams with basaltic reinforcement for the loads 10, 20, 30 kN were equal to 4.2, 7.2, 12.1 mm, respectively, and were about 2.2, 2.4, 3.0 times larger compared to the reference beam deflections (with steel reinforcement).

In the table 3 there are presented chosen tests results of BFRP beams reinforced with 8 mm basalt bars (the maximum loading force Fu and moment MR, fl carried by the beam critical sections and their mean values $F_{u,m}$, $M_{R,fl,m}$, respectively) compared to the results of reference SRC beams with flexural steel reinforcement of the same diameter.

In this table there are also included maximal values of concrete strains ε_1 and ε_7, measured with the extensometer, respectively at 135 mm level from the bottom edge of the beams (in the compression zone) and at a distance of 20 mm (at the level of the flexural reinforcement), as shown in the Fig. 2.

Mean destructive force for reference beams with steel reinforcement was 37,6 kN, whereas for model beams with basalt reinforcement the mean destructive force was equal to 46,7 kN, it means that it was about 24% higher.

Tab. 3. Selected test results of model beams reinforced with basalt bars (BFRP) and reference beams reinforced with steel bars (SRC)

	Steel reinforced reference beams			Basalt reinforced beams		
	SRC1	SRC2	SRC3	BFRP1	BFRP2	BFRP3
F_u, kN	37.5	35.0	40.5	47.5	47.5	45.0
$F_{u,m}$, kN	37.6			46.7		
$M_{R,fl}$, kNm	6.3	5.8	6.8	7.9	7.9	7 .5
$M_{R,fl\,m}$, kNm	6.3			7.8		
ε_1 , ‰	-1.58	-2.17	-2.02	-1.78	-2.60	-3.25
ε_7 , ‰	4.18	5.69	6.52	9.43	13.60	7.76

Summary of research and conclusions

1. 1. It has been confirmed that, in contrast to the bilinear of the stress - strain relationship for the steel reinforcement, the basalt reinforcement has a linear relationship until the failure of the beam.
2. 2. It was noted that critical forces of tested beams reinforced with BFRP bars was much greater than the carrying capacity of beams with conventional reinforcement, which arose from the different degrees of mechanical reinforcement ratio in both types of beams.
3. Destruction of beams with BFRP reinforcement does not occur suddenly and was a result of transformation of the beam into a tie system.

4. Deflections of beams with BFRP reinforcement were significantly higher than the reference beam deflections, due to the much lower modulus of BFRP bars compared to steel bars.
5. Deformations of the basalt flexural reinforcement were considerably higher (average of 3 to 4 times) than the beams with steel reinforcement. However, in the final phase of the load above the difference decreased to 40% due to the phenomenon of plasticity in the beams of conventional steel reinforcement.
6. Due to the relatively lower elasticity modulus of basalt rods, compared to steel ones, both: the deflections and width of cracks can be a major factor in the designing the BFRP reinforced concrete beams.
7. From a practical point of view, in a properly designed BFRP reinforced beam, ultimate moment of capacity due to the tension reinforcement is much higher than the limit of capacity due to the crushing of the concrete.

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