Technical Sciences, 2017, 20(4), 391–404

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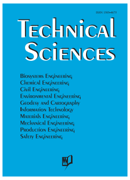
Quarterly peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: www.uwm.edu.pl/techsci/



Technical Sciences

SHEAR BEHAVIOR OF STEEL OR BASALT FIBER REINFORCED CONCRETE BEAMS WITHOUT STIRRUP REINFORCEMENT

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Received 5 May 2017, accepted 24 September 2017, available online 2 October 2017

Key words: shear capacity, basalt fibers, steel fibers, SFRC; BFRC, two-span beams.

Abstract

The paper presents the results of a comprehensive investigation aimed at studying the shear behavior of basalt or steel fiber-reinforced concrete (BFRC or SFRC) beams, as well as analyzing the possibility of using basalt or steel fibers as a minimum shear reinforcement. Two-span reinforced concrete beams with the cross-section of 8×16 cm and length of 200 cm and diversified spacing of stirrups were tested. Steel stirrups or alternatively steel or basalt fibers were used as a shear reinforcement. Steel fiber content was 80 and 120 kg/m^3 and basalt fiber content was 2.5 and 5.0 kg/m^3. The shear behavior and/or bending capacity of SFRC and BFRC beams were studied. The result indicated that fibers can be safely used as a minimum shear reinforcement.

Introduction

The reinforced concrete (RC) beam with either little or no transverse reinforcement can fail prematurely in shear before reaching its full bending capacity. This type of shear failure is sudden in nature and usually catastrophic because it does not give ample warning. Beams are traditionally reinforced with stirrups to prevent shear failures. An alternative solution to stirrup reinforcement is the use of randomly oriented steel fibers, which cause

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Correspondence: Julita Krassowska. Katedra Konstrukcji Budowlanych, Wydział Budownictwa i Inżynierii Środowiska, Politechnika Białostocka, ul. Wiejska 45E, 15-351 Białystok, e-mail: j.krassowska@pb.edu.pl the increase in shear resistance (DINH et al. 2010). Fibers are made from various materials e.g. steel, glass, carbon, basalt or synthetic material.

Concrete with evenly distributed steel fiber reinforcement is the homogeneous material (JASICZAK, MIKOŁAJCZAK 2003). The shape and length of the steel fibers have a great influence on the bearing capacity of composite through adequate adhesion to the concrete. The use of steel fibers in bending elements causes the increase in resistance to cracking, prevents the development of shrinkage cracks and prevents brittle cracking of concrete through the quasi-plastic nature of the structure work. Property of concrete with the addition of steel fibers has the greatest influence on the tensile strength in bending. There was a lot of research on the use of concrete with fibers in Poland. Prefabricated heads regimes of slab pole made of fibers reinforced concrete were tested in the Silesian University of Technology. The studies showed the increase in their capacity to punching (HULIMKA 2009). POGAN (2010) found that the addition of fibers in concrete structures leads to reduction in steel reinforcement bars, as well as to reduction of stirrup number. Research on the possibility of reducing shear reinforcement by adding steel fibers to concrete was carried out in the USA by DINH et al. (2010).

Basalt fibers can also be used as reinforcement in concrete structures. Basalt is natural volcanic material, which is crushed and melted at a temperature 1300–1700°C, then squeezed using special probes into thin fibers. These fibers are coated with a polymer to provide adequate corrosion resistance. Their surface is irregular and rough. These fibers are resistant to corrosion, acidic and alkaline environment due to their chemical composition of the composite. Moreover, basalt fibers are resistant to high and low temperatures, the working temperature range of application ranges from -260°C to +750°C. The dimensions of the fibers are usually as follows: diameter 12 to 18 μ and length of 24–54 mm. Young's modulus of elasticity is in the range of 70–90 GPa, and a tensile strength is between 700–1680 MPa. The composite with this type of fibers is characterized by good mechanical properties (particularly tensile strength) (KOSIOR, KRASSOWSKA 2015). Composites with basalt fiber are used in special structures, such as housing nuclear reactors or facades of tall buildings (JASICZAK, MIKOŁAJCZAK 2003). Basalt composites are used for production of ropes of hanging bridges. ABDULHADI (2014) studied the effect of basalt and polypropylene fibers and concluded that the compressive strength C30/37 concrete with two different type of fiber at different volume fraction. AYUB et al. (2014) studied the material properties of an economical HPFRC containing basalt fibers such as compressive strength, elastic modulus and tensile strength. Experimental results showed that the addition of basalt fibers up to 2% by volume together with mineral admixtures improved the compressive strength. The improvement in the strains corresponding to maximum compressive strength and splitting tensile strength results was observed at all fiber volumes, whereas there was a negligible influence of the fiber addition on the elastic modulus. SMRITI et al. (2013) presented study aims towards mechanical characterization of basalt fiber reinforced composite under compressive loading. The stress strain curve has been determined experimentally for optimal 0.5% volume fraction of basalt fiber reinforced composite and compared with that for unreinforced concrete. CORY et al. (2015) studied the use of basalt fiber bars as flexural reinforcement for concrete members and the use of chopped basalt fibers to enhance the mechanical properties of concrete. Test results indicate that flexural design of concrete members reinforced with basalt fiber bars should ensure compression failure and satisfying the serviceability requirements. ACI 440.1R-06 accurately predicts the flexural capacity of members reinforced with basalt bars, but it significantly underestimates the deflection at service load level. The use of chopped basalt fibers had little effect on the concrete compressive strength; however, it significantly enhanced its flexural strength. JIANG et al. (2014) analyzed the effects of the volume fraction and length of basalt fiber on the mechanical properties of FRC. The results showed that adding basalt fibers significantly improves the tensile strength, flexural strength and toughness index whereas the compressive strength showed no obvious increase. Furthermore, the length of basalt fibers presents an influence on the mechanical properties.

The experimental research on the shear behavior of SFRC beams has been conducted for the past three decades. Most of these test programs have investigated key parameters known to affect shear behavior, including shear span-to-effective depth ratio, longitudinal reinforcement ratio, fiber volume fraction, and concrete compressive strength. However, there are still parameters that have not been extensively investigated (DINH 2010).

The primary objective of the research was to study the shear behavior of double span beams and ultimate shear capacity of SFRC and BFRC beams without stirrup reinforcement and to analyze the possibility of using steel or basalt fibers as minimum shear reinforcement in RC beams.

Experimental program of testing mechanical properties of concrete with fibers

Material and sample preparation

The tests were performed on fine grained cement concrete. The cement (CEM I 42.5 R) content was constant – 320 kg/m^3 and the water to cement ratio of 0.50 was kept constant in all mixes. The river sand, fraction 0–2 mm and the natural aggregate with maximum diameter of 4 mm were used. The maximum size of aggregate was limited to reduce its influence on fracture properties and to provide the homogenous fibers distribution in concrete. The minimum size of sample exceeded the maximum size of aggregate more than tenfold.

Steel fibers (Fig. 1*a*) with hook-shaped ends with a length of 50 mm and a diameter of 1 mm were used for modification of concrete mix. They were characterized by tensile strength of 800 MPa. The test was performed for concrete mixtures with the steel fiber content of 80 and 120 kg/m^3.

The chopped basalt fiber (Fig. 1*b*) length was 50 mm and diameter of 20 μ. Fiber density was 2,650 kg/m^3. They were characterized by high tensile strength of 1680 MPa and Young's modulus of 90 GPa. The tests were carried out with the same composition of the cement matrix and diverse content of basalt fiber 2.5, 5.0 kg/m^3.

The fibres were added into concrete as a replacement of an adequate portion of aggregate by volume. The effect of fibres on mechanical properties was referee to the result obtained for reference concrete without fibres.

The dry aggregate was mixed with fibres followed by cement. The materials were dry mixed for 2 min before adding the water with superplasticizer. Mixing continued for further 4 min. The time of mixing was considered sufficient for the proper dispersion of fibres in the mix without causing a "balling" effect.

The specimens were vibrated in moulds and then stored under polyethylene cover for one day. After demoulding all specimens were cured in water at the temperature of 20±2°C till they were tested.

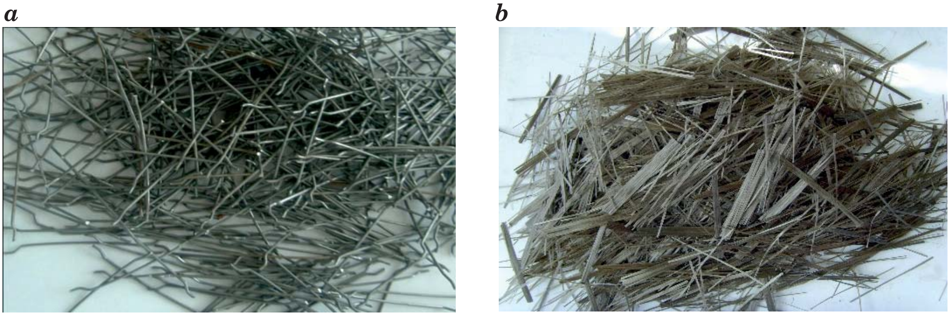

Fig. 1. The types of fiber used for testing: *a* – steel fibers, *b* – basalt fibers

Test methods

Compressive strength f_{ck}, flexural strength f_{ctm} and modulus of elasticity E_s of concretes with fibers were determined. Test of concrete compressive strength f_{ck} was performed according to standard PN-EN 12390-3 (2011) using cubic samples of size 100×100×100 mm. The flexural strength f_{ctm} was determined on samples of size 100×100×400 mm according to PN-EN 12390-5 (2011). Modulus of elasticity was determined according to PN-EN 12390-13 (2014), using cylindrical samples with a diameter of 150 mm and a depth of 300 mm.

Fracture behavior is the most important aspect of FRC. Nominal values of the material properties can be determined by performing a three-point bending test on a notched beam according to f_{ib} Model Code (2010).

The notched beams of size 100×100×400 mm were used in test. The initial saw-cut notch with a depth equal to 30 mm and width of 3 mm was located in the mid-span place. The geometry of sample and the way of load were presented in Figure 2.

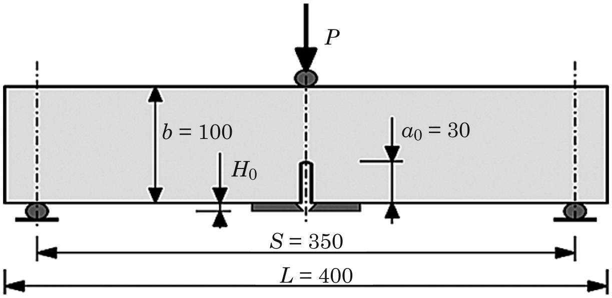

Fig. 2. Dimensions and method of load of test sample (in mm)

The universal testing machine (MTS 322) with closed loop servo control was used to achieve a stable failure of samples. The crack mouth opening displacement (CMOD) measured at the center of the notch was a feedback signal. The clip gauge was used to measure the CMOD values. The load – crack mouth opening displacement (P-CMOD) was determined for fracture behavior analysis in accordance with the general requirements of f_{ib} Model Code 2010.

Results

The test results of compressive strength f_{ck}, mean value of flexural strength of concrete f_{ctm} and modules of elasticity E_s determined after 28 days of curing were presented in Table 1. The steel fibers and basalt showed no significant effect on the compressive strength of concrete. A small increase in f_{ck} could be caused by scatter in the test results. The increase in flexural strength was 52% in the case of concrete with fibers in the amount of 120 kg/m^3. The increase in flexural strength f_{ctm} for concrete counting 5,0 kg/m^3 of basalt fibers was 47% in comparison to concrete without the fibers. Results of research of elastic modulus confirmed that the fibers do not significantly improve the elasticity of concrete.

Table 1

Mechanical properties of concrete with steel and basalt fibers

Type of fibers	Content of fiber	f_{ck}	Δf_{ck}	f_{ctm}	Δf_{ctm}	E_s	ΔE
	[kg/m^3]	[MPa]	[%]	[MPa]	[%]	[GPa]	[%]
Without fiber	0	28	–	4.01	–	28.59	–
Basalt fiber	2.5	30.8	10	5.13	27.93	33.5	17.17
	5.0	31.9	13.93	5.89	46.88	32.83	14.83
Steel fiber	80	29.01	3.61	5.49	36.91	30.53	6.79
	120	31.78	13.5	6.093	51.95	32.11	12.31

The characteristic curves of load P plotted versus CMOD for concretes with steel fibers and without fibers were presented in Figure 3.

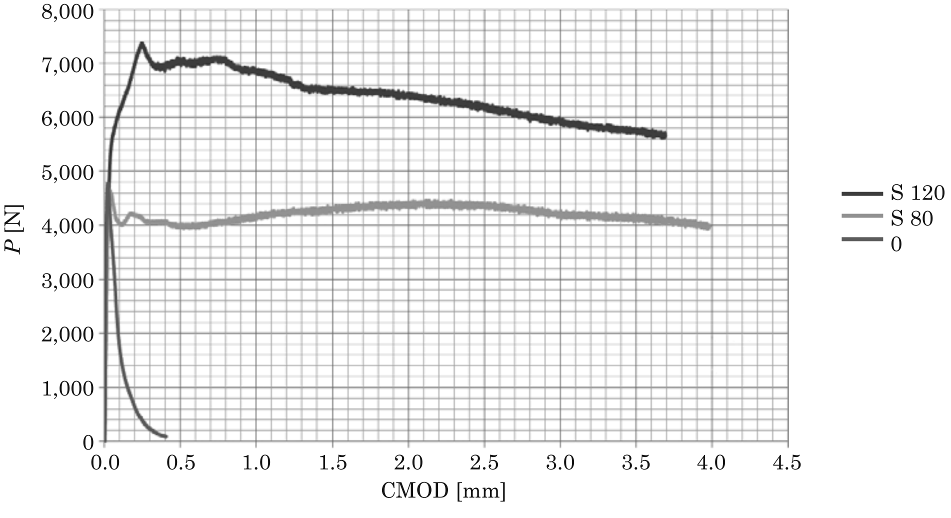

Fig. 3. Load P versus CMOD curves for concretes with various volume fraction of steel fibers and without fibers

The influence of steel fiber addition expresses itself by reaching a higher maximum ultimate load, larger displacement, and thus a larger area under the load-CMOD curve. In a typical load vs. CMOD diagram for sample under three-point loading, the material exhibits linear behavior up to its first crack stress (well marked first peak), a post-first-crack strain hardening phase up to its ultimate flexural load, and a post-ultimate-load phase. The descending parts of diagrams for concretes with different fiber dosage are characterized by apparent nonlinearity and significant scatter of test results. Both the strain softening and hardening were observed.

The characteristic curves of load *P* plotted versus CMOD with basalt fibers and without fibers were presented in Figure 4.

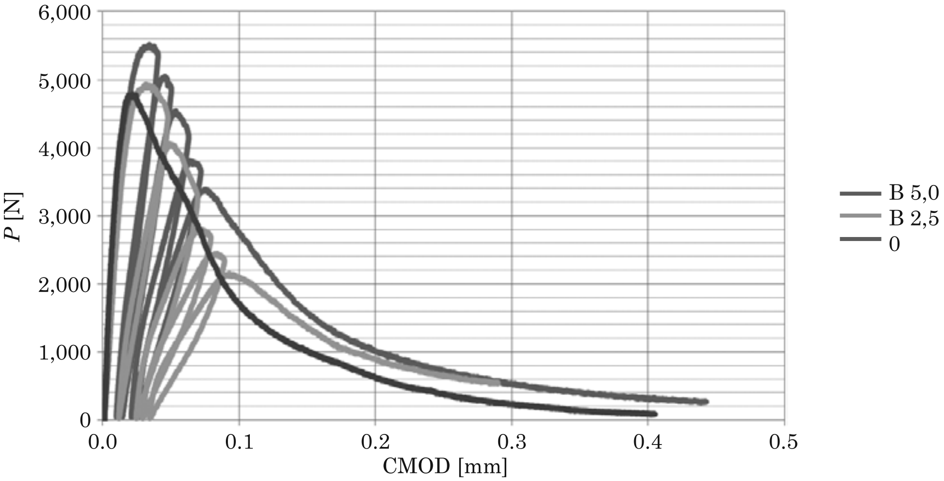

Fig. 4. Load *P* versus CMOD curves for concretes with various volume fractions of basalt fibers and without fibers

The analysis of *P*-CMOD plots for concretes with basalt fibers makes it possible to investigate the changes in concrete properties related to the loss of brittle material character. From the *P*-CMOD diagram, one can see that the initial parts of the curve for all concretes considered are almost linear and the strain of the notch tip under tension increases slightly with the increasing load. After the linear segment of *P*-CMOD curve, deviation from linear response is observed and the load reaches the maximum value, which indicates the onset of crack initiation at the tip of the notch. The increase in basalt fiber content causes the increase in the length of segment until reaching the peak. The crack mouth opening displacement, recorded for maximum load for individual samples, increased when the content of fiber increased. Generally, the $\text{CMOD}_{\max}$ values for fiber reinforced concrete were greater than recorded for control concrete samples. However, the influence of basalt fiber content on the maximum load is not clear. The addition of fiber up to 2.5 kg/m^3 caused the increase in $P_{\max}$, but further increase in fiber content up to 5.0 kg/m^3 caused the decrease in maximum load value.

Experimental program for testing model beams with basalt and steel fibers

Assumptions for the research program of model beams with mixed reinforcement

Five series of double-span model beams with dimensions of 80×180×2000mm were made. Each series contained five different elements of steel and basalt fiber, with different spacing of stirrups (Fig. 5).

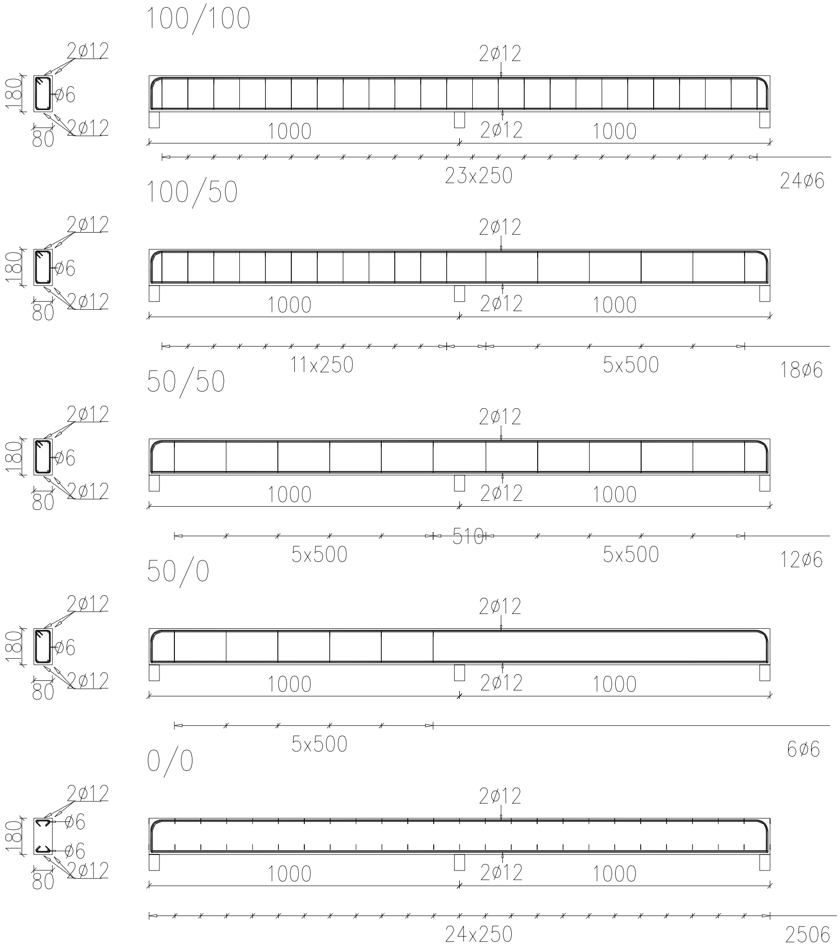

Fig. 5. The reinforcement of beams tested

Steel fibers in the amount of 80 and 120 kg/m^3 and the amount of basalt fibers in the amount of 2.5 and 5.0 kg/m^3 were chosen for testing the model beams. The reference beams of concrete without fibers were also prepared. Calculations of bending and shear reinforcement were performed in accordance with PN-EN 1992-1-1, assuming the force load concentrated in the center of each span. The bending reinforcement was identical in all beams tested and comprised two bars of Φ 12 mm (reinforcement degree of 0,8%) in each test series. A variable spacing of stirrups was used. The first series 100/100 was made with spacing stirrups calculated in accordance with EN 1992-1-1, and then for each series the stirrup spacing was reduced. In series 0/0 stirrup spacing was reduced to zero (beams without stirrups in both spans). The reinforcement of beams was shown in Figure 5.

The influence of fiber on the failure mode

Depending on the type of fibers used in each series, different ways of capacity loss have been observed. The failure mode is strongly dependent on the shear-span/depth ratio (a_v/d). The shear-span/depth ratio was 2.7 in tested beams, that means that beams should fail in shear. Tested elements have been destroyed by crushing the concrete in the compressive zone and large perpendicular cracks caused by bending in the beams of the series S100/100 with steel fibers in an amount of 120 kg/m^3 and B100/100 beams with basalt fibers in the amount of 5.0 kg/m^3 (in which stirrup shear reinforcement provided shear forces). In most cases, the failure was caused by shear in span with reduced spacing of the stirrups. Fail due to shear was similar in all tested beams. As the force increased, the cracks in the support zone would propagate towards the loading point, gradually becoming an inclined crack, which is known as a flexural-shear crack, but which is often referees to simple a diagonal crack. With further increases in force, the diagonals crack tends to stop. Then, near to longitudinal reinforcement random cracks start to occur. With the increase of force, the diagonal crack widens and propagates along the level of the tension reinforcement. The bond between the concrete and the steel was destructed. The beam was destroyed and collapsed. In case of RC beams the collapse was immediate with characteristic "crash" sound. In beams with the addition of steel fibers and basalt fibers destruction process proceeded in a gentle way. First, we observed significant increase in the deflection of beam mid span and an increase in crack width. Test elements with fiber reinforcement showed properties of quasi- plastic material. The beam after the uprising diagonal crack continued to carry loads. The examples of failure of beams were shown in Figure 6.

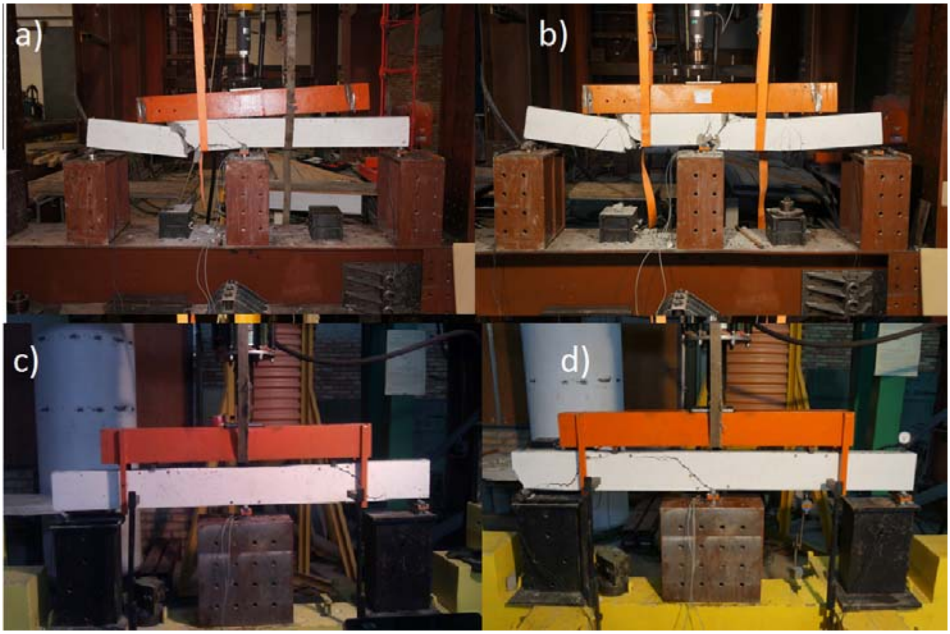

Fig. 6. Destruction of beams with steel fibers series: *a* – S80-50/0, *b* – S120-100/50/100 and basalt fibers, *c* – B2,5-50/50, *d* – B5,0-0/0

The effect of fibers on the shear capacity of beams

In the studies, reactions at the supports, as well as the total load of destruction were measured. The values of destructive forces and their increments compared to the values of the destructive forces for the reference beams (without fiber) were presented in Table 2. In the case of SFRC beams, the increase in destruction force volume was from 36.5% to 100.7%. In the case of BFRC the growth of destruction force was from 14.2% to 54.0%. The maximum increase in shear capacity was observed for beams of series S120-50/0. Beams series 50/50 with both basalt (5.0 kg/m^3) and steel (120 kg/m^3) fibers carried the same (or larger) destroying load as the beam series 100/100 without fiber only with stirrups reinforced.

The effect of fibers on support reactions

In test the dependence of the support reactions on the load in the tested beams series 50/0 (right span without stirrups, left span with stirrups in reduced spacing) was showed. Beams series 50/0 with addition of steel or basalt fibres and reference beam were presented in Figure 7.

Table 2

Destructive forces and their percentage increase for beams tested

Series	Beam with basalt fiber	Destructive force	Increase in force	Beam with basalt fiber	Destructive force	Increase in force
		[KN]	[%]		[KN]	[%]
100/100	B0-100/100	80.6	–	S0-100/100	80.6	–
	B2.5-100/100	95.3	18.2	S1.0-100/100	110.0	36.5
	B5.0-100/100	106.7	32.4	S1.5-100/100	114.71	42.3
00/50	B0-100/50	57.8	–	S0-100/50	57.8	–
	B2.5-100/50	70.2	21.5	S1.0-100/50	93.4	61.6
	B5.0-100/50	75.3	30.3	S1.5-100/50	109.7	89.8
50/50	B0-50/50	60.7	–	S0-50/50	60.7	–
	B2.5-50/50	69.3	14.2	S1.0-50/50	64.1*	–
	B5.0-50/50	93.5	54.0	S1.5-50/50	102.7	69.2
50/0	B0-50/0	29.9	–	S0-50/0	29.9	–
	B2.5-50/0	33.5	12.0	S1.0-50/0	47.6	59.2
	B5.0-50/0	44.1	47.5	S1.5-50/0	60.0	**100.7**
0/0	B0-0/0	33.1	–	B0-0/0	33.1	–
	B2.5-0/0	37.9	14.5	S1.0-0/0	47.0	42.0
	B5.0-0/0	49.4	49.2	S1.5-0/0	52.8	59.5

* – beam was lateral-torsional buckling, 1 – beam was destroyed by bending

In the case of beam 50/0 without fibres, the all reactions with the increase in load had comparable values. The beam has been destroyed by shearing in the right span. There was only one main diagonal crack on the extreme support, which developed from the perpendicular cracks. The diagonal propagation was then followed in the direction of load application and in the direction of the level of the longitudinal reinforcement, and in the final stage also along the longitudinal reinforcement towards the support. The beams have been destroyed by shearing as a result of a sudden diagonal crack.

The beams of the series S120-50/0 or B5,0-50/0 have been destroyed at the centre support. The response on the centre support was much higher than for the rest of supports, meaning that most of the load has been transmitted by the centre support (here the plastic prosthesis has been created). For the series S120-50/0 in the initial phase of the load one can see the redistribution of transverse forces. After levelling forces at supports and cracks in the spans, the centre support took over the load transfer. In the beams of the series S120-50/0 or B5,0-50/0, the first cracks were orthogonal in the middle of the spans. As the load increased, more orthogonal cracks were created and their propagation at the sectional height took place. The slow and stabilized development of the perpendicular cracks was observed until diagonal crack appeared on the centre

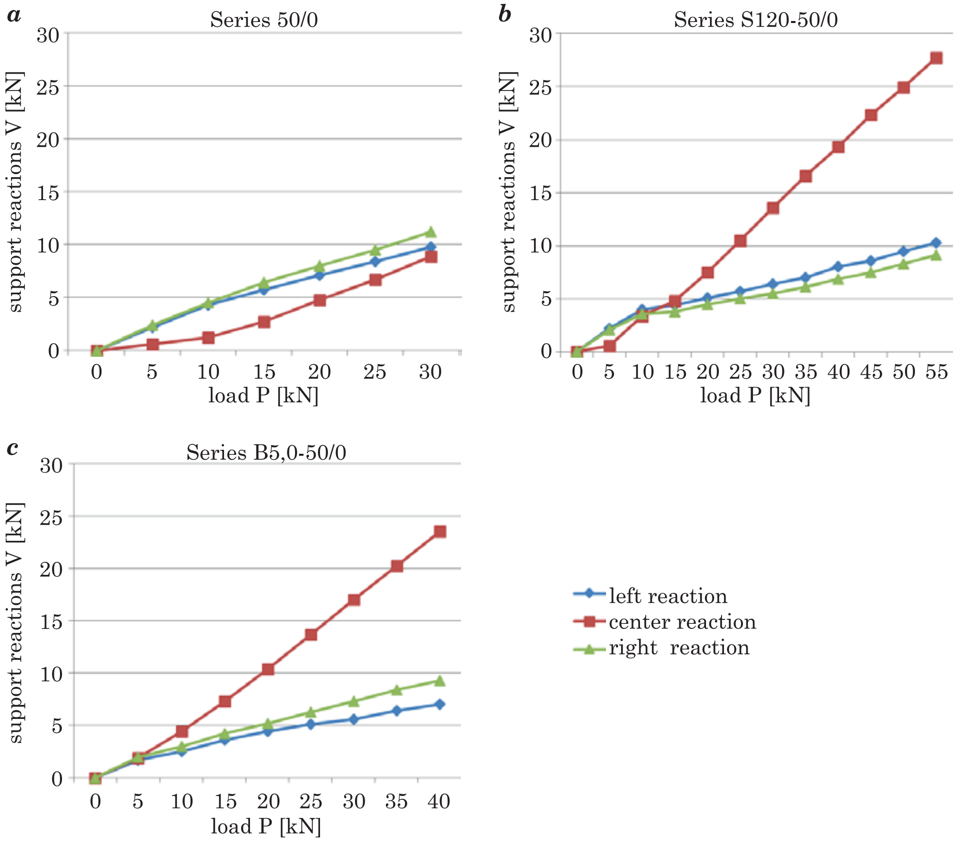

Fig. 7. A graph of the dependency of the support reaction to the load: *a* – 50/0 steel fibers, *b* – S120-50/0 and basalt fibers, *c* – B5,0-50/0

support at the side with reduced number of stirrups. Through the redistribution of internal forces, the central support has become the most loaded and external supports had similar values.

Conclusions

Steel fibers and basalt fibers had the slight impact on the compressive strength of concrete. In the case of flexural strength the changes were much bigger, for basalt fibers the maximum increase was 47% and for steel fiber similar increase was 51.95%.

The incorporation of considered volume fraction (2.5–5.0 kg/m^3) of thin, soft basalt fibers had an influence on concrete element improvement of pre-peak and post-peak behavior.

The stiff, hooked-end steel fibers (incorporated in the volume fraction of 80 and 120 kg/m^3) influenced concrete performance more efficiently than basalt fibers. The flexural tensile strength and the ductility increased with increasing fiber volume as expected. Steel fibers had relatively slight effect on pre-peak behavior of concrete samples. These parts of load-CMOD plot were more linear in comparison to plots obtained for basalt fiber reinforced concrete. In this phase, the steel fibers were particularly effective in the elimination of influence of pores and other microstructure defects on concrete sample behavior under load. The stable post-peak performance at larger CMOD values was dominated by the volume of steel fibers due to the presence of the hooks and its large embedded length.

Studies of double-span reinforced concrete beams showed the increase in shear capacity, increasing with the increase in fiber content. The increase in shear capacity for series tested was approx. 100% for steel fiber reinforcement and approx. 50% for basalt fiber. The lowest ultimate shear capacity for the SFRC and BFRC beams was still 2.5 and 1.5 times greater than that for the control RC beams. Although the lowest normalized shear strength for the beam series corresponded to one of the test beams with the smallest amount of fibers and reinforcement ratio (Beam 0/0). The results confirm the possibility of using the steel or basalt fibers as a minimum shear reinforcement in RC beams.

Acknowledgements

Studies have been carried out under the project ID 245084 funded by the National Centre for Research and Development.

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