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Experimental and numerical assessment of size effect in geometrically similar slender concrete beams with basalt reinforcement

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ABSTRACT

The paper presents a comprehensive experimental and numerical analysis of slender rectangular reinforced concrete beams with longitudinal BFRP bars without shear reinforcement subjected to 3-point bending. The experiments included 4 different beams which were similar in two directions. The main research objective was to investigate the size effect on the nominal shear strength of beams. The detailed experimental analysis of beam strength, failure mode and cracking evolution was presented and compared with previous test results on beams reinforced by ordinary steel bears. The experiments with BFRP bars were numerically reproduced using the 2D finite element method based on a coupled elastic-plastic-damage formulation. In order to describe strain localization in concrete, a non-local constitutive model was applied with account for a characteristic length of micro-structure developing in the softening regime. The numerical results were in satisfactory agreement with the experimental data. Advantages and disadvantages of BFRP reinforcement in concrete beams were next outlined.

1. Introduction

Composite reinforcement is an interesting and attractive alternative to conventional steel bars reinforcement since it significantly increases the structure durability due to its high corrosion resistance. In particular, it is perfect for marine environments and chemical plants where corrosion is a continuous concern. Thus it follows the principles of sustainable development. For instance, basalt fiber reinforced polymers (BFRP) belong to composites, recently becoming more popular in the world. The reinforcement is made of volcanic rock basalt, found throughout the world where volcanoes have erupted and sent lava to the surface. Basalt bars may be smooth and ribbed, with the diameter up to 20 mm. They can also be produced as ropes, tendons, and grids in a wide variety of shapes and surface configurations with varied characteristics. Other excellent characteristics of basalt reinforcement are: high tensile strength up to 1′100 MPa (rupture strain 2.2%), low weight (mass density of 1.9 g/cm^3), resistance to alkali, acids, radiation and UV light, electromagnetic, electric and electrostatic indifference, high heat stability, good environmental friendliness (no environmental waste), non-toxicity in use or recycling and low water absorption. The basalt reinforcement has the same thermal expansion coefficient as concrete. It may be easily cut to required length with regular tools. The disadvantages of this reinforcement are: low elastic modulus (40–70 GPa), lack of yielding before rupture (failure is perfectly brittle), low resistance to fire (due to the resin presence), low resistance to shear, compressive strength lower by 20–50% than tensile strength, occurrence of static fatigue, weaker bond to concrete. The reinforcement quality strongly depends upon the production method inducing a higher price (basalt bars are ca. 4 times more expensive on average than traditional steel bars). When designing concrete elements reinforced with basalt bars subjected to bending, the American code ACI 440.1R-03 [1] may be used. The flexural strength is dependent on the failure mode, governed by concrete crushing or by bar rupture. The first failure mechanism is desired since the failure mode of basalt bars is perfectly brittle. The procedures to calculate the flexural shear strength, deflection and crack width follow the same rules as for conventional steel-reinforced beams.

There are many research works on mechanical properties of concrete beams with BFRP bars in the literature (e.g. [2–7]). They focused mainly on the flexural behaviour of beams in service and in their ultimate limit states, by considering two basic failure modes, i.e. concrete crushing or bars rupture [2,3,5]. The effect of the reinforcement ratio on the strength, cracking

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and deflection was studied in [3,5,6]. The results were compared with different concrete code provisions [5,6]. The researchers indicated large deflections and wide cracks in concrete beams with basalt bars [2,4,6,7]. The concrete beams were also simultaneously reinforced with basalt and steel bars in order to diminish deflections [4]. In addition, basalt stirrups were used which increased the strength of beams with steel stirrups and changed the failure mode from flexure to shear [5]. The effectiveness of basalt bars in concrete beams may significantly increase when they are prestressed [7].

This purpose of the paper is twofold: (1) comprehensive experimental size effect investigations aimed at assessing the mechanical characteristics of geometrically similar slender concrete beams with longitudinal basalt reinforcement (without shear reinforcement) failing by shear under three-point bending and (2) two-dimensional numerical description of experimental data by using the finite element method (FEM) based on a coupled elasto-plastic damage constitutive model with non-local softening. In experiments, the fracture process (inherently connected to the size effect) was precisely described by determining the height, width and spacing of cracks. The height and width of localized zones were determined by means of the digital image correlation (DIC) technique. The innovative points of our investigations are as follows: (a) assessment of the usefulness of basalt reinforcement regarded as structural in slender concrete beams under bending and (b) experimental and numerical analyses of the size effect in concrete beams with basalt bars and (c) comparative studies regarding a size effect in concrete beams with longitudinal basalt and steel bars [8]. Our experimental study is a continuation of the earlier size effect tests on short concrete beams with basalt reinforcement [8]. To our knowledge there are no other research works on the size effect of the shear strength in geometrically similar concrete beams reinforced with BFRP reinforcement.

The outline of the present paper is as follows. First, after the introduction (Section 1), the experimental set-up is described in Section 2. The experimental results on the size effect are described and discussed in Section 3. In Section 4 the numerical model for concrete and reinforcement is presented. The simulation results are discussed in Section 5. The size effect outcomes are described in Section 6. The bar costs are listed in Section 7. The final conclusions are stated in Section 8.

2. Experimental set-up, materials and test procedure

The experimental program involved 4 series of two-dimensionally similar slender concrete beams of a rectangular cross-section subjected to three-point bending (Fig. 1, Table 1). The beams were scaled in two dimensions: length and height (in the proportion 1:2:3:4). The beam thickness was always the same $b = 250$ mm in order to avoid size effects caused by heat conduction and drying [9]. The beams were simply supported. They were classified according to their effective height D and denoted as: D15 ($D = 15$ cm), D30 ($D = 30$ cm), D60 (D=60 cm) and D90 ($D = 90$ cm). Each series included two beams in order to check the result repeatability. The beams were denoted as D15.1 and D15.2, D30.1 and D30.2, D60.1 and D60.2, and D90.1 and D90.2. The ratio of the shear span a and effective depth D was always constant $a/D = 3$. The smallest beam D15 was 197 mm high, 1500 mm long and its effective span length was 900 mm. The biggest beam D90 was 981 mm high, 6040 mm long and its effective span length was 5400 mm. There were no stirrups in the beams. The reinforcement ratio $\rho = 0.845\%$ ($\rho = A_l/bD$, A_l – the total cross-section area of reinforcement) was designed to be high enough to prevent the beam failure due to flexure (bars rapture) and to induce failure due to diagonal tension. It was obtained by applying a different number of basalt bars with the same diameter ($\phi = 14$ mm) (the cross-section of bars was not scaled). A two-dimensional geometrical similarity of concrete beams and different number of bars of the same diameter is frequently assumed in experiments on size effect (see e.g. [10–14]).The reinforcement of the beams D15 and D30 consisted of 2 and 4 bars in one row at the beam bottom (Fig. 2, Table 2). The reinforcement for the series D60 was composed of 8 bars in 2 rows while the reinforcement for the series

Table 1
Dimensions of slender concrete beams with BFRP bars (symbols described in Fig. 1).

Dimension	Concrete beams			
	D15	D30	D60	D90
H [mm]	197	347	664	981
D [mm]	150	300	600	900
L [mm]	1500	2400	4200	6040
L_{eff} [mm]	900	1800	3600	5400

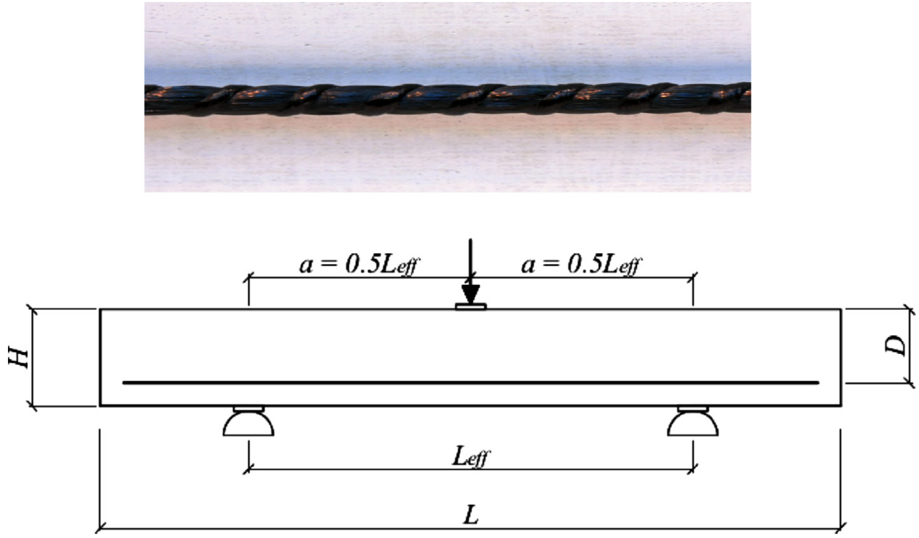

Fig. 1. View of basalt BFRP ribbed bar and static scheme of slender concrete beams under 3-point bending (H – beam height, L – beam length, L_{eff} – beam span, D – effective beam height, a – shear span).