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Research Article

Experimental Investigation on the Ductility of Concrete Deep Beams Reinforced with Basalt-Carbon and Basalt-Steel Wire Hybrid Composite Bars

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Using steel bars in corrosive conditions imposes a high cost on concrete elements. This is due to corrosion of steel bars. In order to eliminate this issue, the use of composite materials in civil engineering practices has become an area of focus because of their acceptable mechanical behavior, such as high strength, suitable durability in corrosive environmental conditions, and low weight. However, composite bars show low ductility and brittle fracture in tensile tests. These weaknesses act as a stumbling block to the widespread use of such bars in concrete elements. Therefore, a new generation of hybrid composite bars, fabricated by a combination of two or more composite fibers, has been proposed to eliminate these downsides. In this research project, six reinforced concrete beams in three groups, including beams reinforced with basalt-wire hybrid composite bars, carbon-basalt hybrid composite bars, and steel bars, have been evaluated in statistical 4-point flexural tests. The test results showed that the energy absorption rate for beams reinforced with basalt-wire hybrid bars compared to beams reinforced with steel bars was up to 93% in the statistical 4-point flexural test.

1. Introduction

Steel bars have many weaknesses in aggressive environmental conditions due to corrosion [1]. These weaknesses, in the long run, cause damages to concrete elements. The very epitome of such weaknesses is cracking and loss of concrete cover and reducing the function of concrete elements [2, 3]. Various methods have been proposed by researchers to eliminate these weaknesses. One of the proposed methods is using a hybrid system in which steel bars and composite bars are used in concrete elements simultaneously [4–7]. Zadeh and Nanni [8] presented a theoretical method to investigate the behavior of concrete elements reinforced with composite glass fiber-reinforced polymer (GFRP) bars under simultaneous bending and axial forces. Ferreira et al. [9] showed that the cross-sectional shape of composite bars plays an essential role in the behavior of concrete elements. Almusallam [10] proposed a numerical method for predicting the bending behavior of beams reinforced with FRP bars. Toutanji and Deng [11] evaluated the cracks' width in 6 specimens of concrete beams reinforced with GFRP bars.

Using composite bars instead of using steel ones eliminates bars' corrosion in concrete elements because this type of bars has acceptable mechanical properties, such as high environmental durability and high resistance to corrosion [9, 12]. However, using such bars is limited due to their low elastic modulus and also their low ductility [13, 14]. Therefore, utilizing hybrid composite bars that are made from 2 or more fibers is proposed to deal with these weaknesses. Mirdarsoltany et al. [15] made hybrid composite bars using steel bars and glass fibers. This type of bars had an elastic modulus of 96 GPa and tensile strength of about 790 MPa. Ma et al. [16] fabricated hybrid composite bars with steel bars and basalt fibers. The test results showed that hybridization makes an improvement in the elastic modulus of this type of bars compared to GFRP bars. Cui and Tao [17] made only one type of hybrid composite bars using carbon, Twaron, glass, and steel fibers, which were much more resistant to corrosion than steel bars, and they had an elastic modulus of 142.11 GPa and tensile strength of 628 MPa. Two types of hybrid composite bars using carbon and glass fibers were made by Liang et al. [18]. In the first type, carbon fibers were placed in the core of the bar and glass fibers around it, and in the second type, carbon fibers were distributed irregularly in the cross section of the bar. These specimens were evaluated under a one-way tensile test. Test results showed a yield point of 1153 MPa and tensile strength of 1191 MPa with a final strain of 3.5%.

Seo et al. [19] investigated the effect of the hybridization process on the elastic modulus of composite bars made of glass fibers, which showed a 270% increase in elastic modulus compared to GFRP bars. Hwang et al. [20] evaluated two specimens of hybrid bars with diameters of 13 and 16 mm and the percentage of steel wires with diameters of 0.5, 1, and 2 mm with steel ratios of 10, 30, 50, and 70%. The results showed an increase in the elastic modulus of hybrid composite bars from 20 to 190% compared to GFRP bars. Correia et al. [21] built two types of glass-steel and basalt-steel composite hybrid bars and compared their tensile behavior results with GFRP bars [22]. The results of the specimens showed that this process caused nonlinear behavior in these types of hybrid composite bars [23]. Since few tests have been performed on evaluating the performance of hybrid composite bars in concrete elements, in this research project, four specimens of concrete beams reinforced with hybrid composite bars were investigated under statistical four-point flexural tests [24]. Moreover, results were compared with 2 specimens of beams reinforced with steel bars.

2. Materials and Methods

Six concrete beams reinforced with hybrid composite bars and steel bars were evaluated. All the specimens were subjected to a statistical four-point flexural test, and the test variables are the type of bars used in the sections.

2.1. Bars. For reinforcing all of 6 specimens, steel bars with a diameter of 10 mm are used as compression bars, and also, bars with a diameter of 8 mm are used as transverse reinforcements . For longitudinal bars in the tensile area of the beam, steel bars with a diameter of 10 mm are used as a control specimen. Six numbers of hybrid bars in 2 types (basalt-wire bars and carbon-basalt bars) with a length of 950 mm and diameter of 10 mm were fabricated by a hybridization process and then used as a reinforcement for concrete beams. In basalt-wire hybrid composite bars, 22% of the cross-sectional area was made of steel wires with a diameter of 1.5 mm, and 78% of bars' cross section were basalt roving [25]. It should be noted that the volume of the resin was not considered [26]. The carbon-basalt hybrid composite bars were made of carbon and basalt composite fibers. Carbon roving fibers were used in the bar's core and basalt roving fibers were placed as the core coating [27]. The mechanical properties of materials used in the fabrication of hybrid composite bars were obtained from tensile tests, and their results are shown in Table 1. The mechanical behavior of bars used for reinforcing concrete specimens is shown in Table 2. It should be noted that hybrid composite bars were tested in accordance with ACI 440K standards.

Figures 1 and 2 show the strain-stress diagram of basalt-carbon and basalt-steel hybrid composite bars obtained from the tensile tests. Figure 3 shows a tensile test of hybrid composite bars.

It should be noted that, to increase the adhesion of hybrid composite bars and the concrete surface, bars' surfaces were covered with a sand coating method to prevent these bars from slipping during the four-point test. Figure 4 shows the surface of hybrid composite bars.

2.2. The Concrete. The compressive strength of concrete was measured at 41 MPa on the day of the test. Figure 5 shows $150 * 300$ mm standard cylinder for measuring the compressive strength of concrete on the day of the test.

2.3. Test Specimens. The concrete beams were 250 mm high, 150 mm wide, and 1000 mm long. The stirrups used to prevent shear rupture are placed 100 mm apart. The amount of concrete cover was 27.5 mm for all concrete beam specimens. All beams are designed based on the rupture of the longitudinal bars used. Figures 6 and 7 show details of concrete beam specimens. Specimens of concrete beams reinforced with basalt-wire, carbon-basalt, and steel hybrid bars are shown in Table 3.

2.4. Loading Beams. Beams were subjected to the four-point flexural test by using the Schenck machine. The capacity of the device was 600 KN, and loading was done using hydraulic rams [28]. These rams are also based on the speed of movement as the input [29]. Therefore, after receiving this speed, the machine records the amount of force applied to the ram per shift, and finally, the output will be the load-displacement diagram. The displacement is related to the main ram. The 4-point flexural test is designed in which the area between two loading rams is subjected to pure bending. Figure 8 shows the loading of concrete beams. Moreover, it should be noted that, according to ISIS module 3, all specimens were designed based on failure of longtitude reinforcement.

3. Results and Discussion

3.1. Test Results of Concrete Beams. As mentioned in the previous section, in this research project, six specimens of concrete beams with specific dimensions were subjected to the 4-point flexural test. In this test, the force-displacement diagram of the beam was obtained via using a Schenck machine.

3.2. Comparison of Force-Displacement Diagrams of Reinforced Concrete Beams. As shown in Figure 8, the force-

Table 1: Mechanical properties of materials used to fabricate hybrid composite bars.

Materials	Tensile strength (MPa)	Elastic modulus (GPa)	Tensile elongation (%)
Carbon T300 fibers	1230–1540	225	1.25–1.5
Basalt fibers	1050–1100	72	2.8–3
Steel wires	1270–1470	200	—
Vinyl ester 901	75	3	4.5–5

Table 2: Mechanical specifications of bars used in concrete beams.

Materials	Tensile strength (MPa)	Elastic modulus (GPa)
Basalt-wire	1027	55
Carbon-basalt	869	106
Steel	1180–1370	200

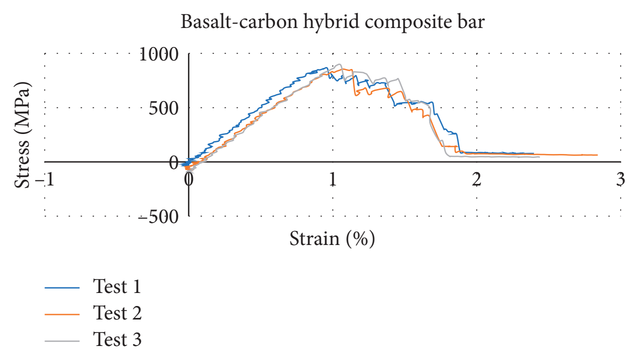

Figure 1: Stress-strain diagram of basalt-carbon hybrid composite bars.

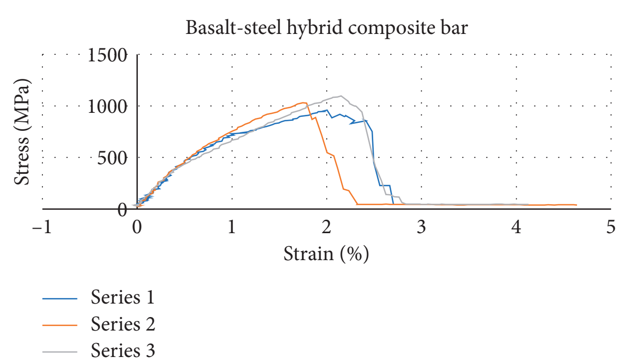

Figure 2: Stress-strain diagram of basalt-steel hybrid composite bars.

displacement diagram of the beams reinforced with basalt fibers and steel wire shows acceptable energy absorption and entry into the linear zone. These specimens also have a higher bearing capacity compared to a beam reinforced with steel bars. Figure 9 shows the cracks created in the concrete beam reinforced with basalt-wire hybrid composite bars. Unlike the beam reinforced with the hybrid composite bars made of basalt fibers and steel wire, the beam reinforced with hybrid composite bars made of carbon fibers and basalt does not exhibit good ductility behavior. It should be noted that this specimen has a higher bearing capacity compared to other beams. Figure 10 shows the cracks created in the concrete specimen reinforced with the carbon-basalt hybrid composite bar. Figure 11 shows the mean value of the force and displacement of concrete beams.

3.3. The Amount of Energy Absorbed in Concrete Specimens. To calculate the energy absorbed by each of the specimens, the area under the force-ductility diagram of each beam is calculated, which is shown in Table 4. In order to compare the ductility of beams, ductility-based methods in beams reinforced with nonsteel bars are not applicable due to the

Figure 3: Tensile test of hybrid composite bars.

Figure 4: The surface of hybrid composite bars.

Figure 5: Measuring compressive strength of concrete using standard cylinders.

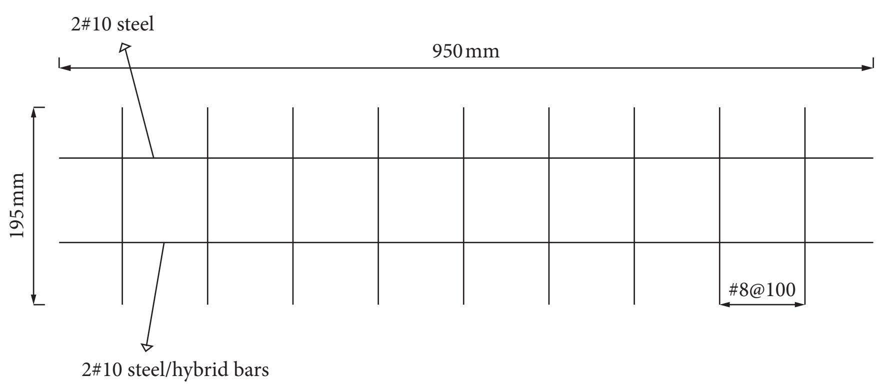

Figure 6: How to reinforce concrete specimens.

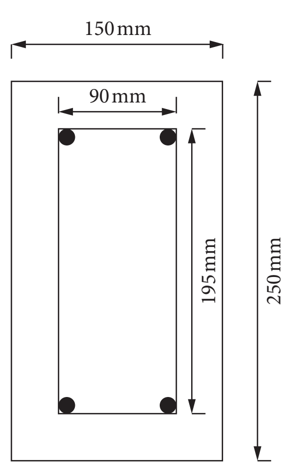

Figure 7: Cross section of concrete specimens.

Table 3: Specifications of built concrete beams.

Specimen ID	$f'c$ (MPa)	A_f (mm^2)
Basalt-wire	41.2	78.5
Carbon-basalt	40.8	78.5
Steel	41.3	78.5

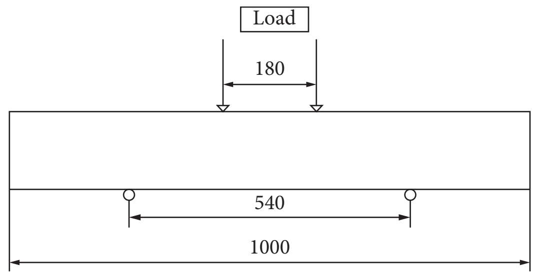

Figure 8: Four-point flexural loading of concrete beams.

Figure 9: Cracks made in the concrete beam reinforced with the basalt-wire hybrid composite bar.

Figure 10: Cracks created in a specimen of the concrete beam reinforced with the carbon-basalt hybrid bar.

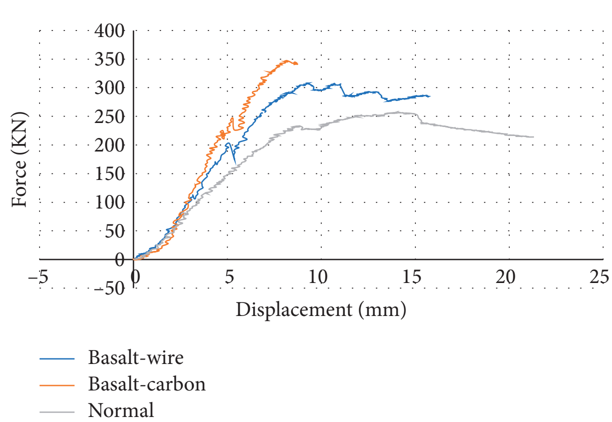

Figure 11: Results of the 4-point flexural test of reinforced concrete beams.

Table 4: The amount of energy absorbed by reinforced concrete beams.

Beam ID	Absorbed energy (J)	Relative energy absorbed
Steel bar-reinforced beam	5812.021	—
Basalt-wire bar-reinforced beam	5439.252	0.93
Carbon-basalt bar-reinforced beam	2920.322	0.5

lack of a specific yield point of the hybrid composite bars. In order to evaluate the amount of energy absorbed by the beam, the area under the load-displacement diagram can be calculated. The area below this diagram is equal to $\int_0^{d_u} F \cdot dl$. In this equation, d_u is the final rise of the section, dl is the differential rise, and F is the ram force.

4. Conclusion

In this research project, force-displacement diagrams of 4 concrete beams in two groups, including beams reinforced with carbon-basalt and beams reinforced with basalt-wire hybrid composite bars, were compared with the force-displacement results of beams reinforced with steel bars under the four-point test. Beams reinforced with basalt-wire hybrid composite bars showed ductile behavior during rupture and had about 1.2 times higher bearing capacity compared to steel bar-reinforced concrete beams. In concrete beams reinforced with carbon-basalt hybrid composite bars, the specimen did not show ductile behavior at rupture, and the rupture was sudden, but compared to the reinforced concrete specimen with the steel bar, it had a bearing capacity of about 1.3 times higher. Compared to concrete beams reinforced with steel bars, beams reinforced with basalt-wire and carbon-basalt hybrid composite bars showed less displacement in the 4-point flexural tests, and this value was about 21.3 mm, 15.7 mm, and 8.7 mm, respectively. Comparing the energy absorbed in beams reinforced with basalt-wire and carbon-basalt hybrid bars, the energy absorption rate of beams was 95% and 50% of concrete beams reinforced with steel bars, respectively.

Data Availability

Requests for access to these data should be made to the corresponding author (amin.st@aut.ac.ir).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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