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Experimental and Numerical investigation of Short Concrete Columns Reinforced with BFRP bars under Concentric Loading

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ABSTRACT

Fiber-reinforced polymer (FRP) bars are being examined as a feasible alternative to solve the problem of corrosion in reinforced concrete infrastructure due to their non-corrosive nature. Numerous experimental investigations have been conducted to assess the role of fiber-reinforced polymer bars in concrete columns. Current guidelines have not included the significant insights offered by these investigations, therefore they either ignore or assess the role of FRP bars in compression conservatively. Basalt fiber-reinforced polymer (BFRP) bars have recently emerged as a viable substitute for Glass fiber-reinforced polymer (GFRP) bars and Carbon fiber-reinforced polymer (CFRP) bars since they have higher tensile strength than GFRP and a cheaper cost than CFRP. Because there has been little study on BFRP, it has not been included in the design recommendations. Consequently, the purpose of this work is to quantify the contribution of BFRP bars to the load-carrying capacity of compression members by an experimental and numerical investigation. The longitudinal reinforcement ratio and rebar material are variables in this study. It is found that BFRP bars contribute 15%, which is 32% less than that of steel bars. As the longitudinal reinforcement ratio increases, so does the contribution of BFRP bars. The load-carrying capacities predicted by design equations and numerical models are found to be in good agreement with the experimental results. In conclusion, this study establishes that Basalt Fiber-Reinforced Polymer (BFRP) bars exhibit considerable contribution in compression members.

KEYWORDS: BFRP bar, Corrosion-resistant, Alternative materials, Reinforced Concrete, Numerical Study

1. INTRODUCTION

Corrosion of internal reinforcement in hostile environments seriously threatens the service life of reinforced concrete structures. In order to address this threat, the use of fibre-reinforced polymer (FRP) bars is considered as a possible solution due to its non-corrosive nature. The use of FRP as reinforcement is known to be used in Russia back in 1975 [1]. Since then, significant research has been conducted and several guidelines have been developed around the world by different institutions and organizations.

Several experimental research have been carried out to evaluate the role of FRP bars in concrete columns. According to these studies, when glass fibre-reinforced polymer (GFRP) bars are utilized, their contribution to column capacities ranges from 3 to 14 percent [2]–[10], whereas carbon fibre-reinforced polymer (CFRP) bars provide 6 to 19 percent of total column capacity [4], [11], [12]. Current guidelines [13], [14] have not incorporated the valuable insights provided by these studies so these guidelines either neglect or conservatively consider the role of FRP bars in compression; therefore, more research is required in this area in order to revise the guidelines appropriately.

As a potential substitute for glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) bars, basalt fiber-reinforced polymer (BFRP) bars have recently gained attention due to their superior tensile strength and relative affordability when compared to GFRP and CFRP [15]. Limited research is available on BFRP so it has not been incorporated into the design guidelines. Therefore, in this study, experimental investigation is carried out to quantify the contribution of BFRP bars in compression members. A part from experimental study, numerical investigation was also carried out to get valuable insights.

2. EXPERIMENTAL PROGRAM

A detailed experimental program was designed to study the contribution of BFRP bars in short concrete columns under concentric monotonic loading. A total of four specimens were cast with two replicates each; comprising plain concrete specimens, specimens reinforced with steel bars, and specimens reinforced with BFRP bars so that the contribution of BFRP bars can be evaluated in comparison to plain concrete specimens and steel RC columns. Table 1 shows the test matrix of the experimental program. Figure 1 shows the reinforcement cages while Figure 2 shows the concreting and curing of specimens.

Table 1: Experimental program of the study

Specimen Nomenclature	Replicates	Size (mm)	Height (mm)	fc' (MPa)	Longitudinal Reinforcement			Transverse Reinforcement	
					Material	Detail	ρ (%)	Material	Details
Plain	2	150x150	600	23.1	-	-	-	-	-
S10	2	150x150	600	23.1	Steel	4 Φ10mm	1.40%	Steel	Φ10mm @ 150 mm
B10	2	150x150	600	23.1	BFRP	4 Φ10mm	1.40%	Steel	Φ10mm @ 150 mm
B14	2	150x150	600	23.1	BFRP	4 Φ14mm	2.74%	Steel	Φ10mm @ 150 mm
B20	2	150x150	600	23.1	BFRP	4 Φ20mm	5.59%	Steel	Φ10mm @ 150 mm

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Figure 1: Reinforcement cages

(a) Ready mix concrete

(b) Concreting of specimens

(c) Cast specimens

(d) Curing of specimens

Figure 2: Casting of specimens

3. EXPERIMENTAL RESULTS

The results of the tests are given in Table 2 and depicted in Figure 3. It shows that BFRP bars show less contribution in concrete columns as compared to steel bars. The contribution of BFRP bars is determined to be 15%, which is 32% less than the contribution made by steel reinforcement, which is 22%. With an increase in longitudinal reinforcement ratio, the contribution made by BFRP reinforcement is found to be increased as can be seen in the B14 and B20 in comparison to B10. The failure load of B20 is less than B14 which is contrary to the trend. Most probably, in this sample, the concrete strength of concrete has been compromised.

Table 2: Experimental results of the tested specimens

Specimen Nomenclature	Ultimate Failure load (kN)
Plain	441.69

S10	540.95
B10	510.08
B14	541.50
B20	520.99

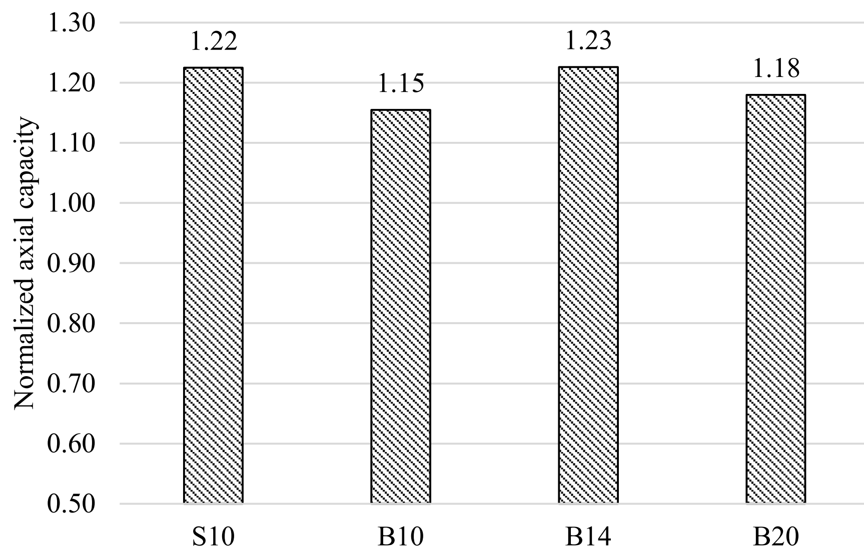


Figure 3 Axial load-carrying capacities of concentrically loaded columns normalized to plain concrete specimen

Figure 4 depicts the failure mechanisms of tested specimens. All of the specimens showed compression-controlled failure mode owing to concrete crushing with some cover spalling. In the examined specimens, there is no observation of buckling or crushing of the bars.

S10 B10 B14 B20

Figure 4: Failure pattern of tested specimens

4. PREDICTING LOAD-CARRYING CAPACITY USING DIFFERENT DESIGN EQUATIONS

The load-carrying capability of BFRP RC columns was predicted using various design equations. It has to be noted that checking the applicability of these equations on BFRP RC column is another key aspect since these equations are based on the dataset of either GFRP or CFRP bars. There are a total of three approaches that can be employed as reported in the literature. First, assuming that FRP bars do not contribute to the column's capacity. Secondly, by taking into account the FRP bars' contribution in the context of their decreased compressive strength. Third, by taking into account the FRP bars' contribution depending on the ultimate concrete strains. Table 3 contains a set of the design equations along with pertinent references.

Table 3: Some of the design euqations for FRP-RC column available in literature

References	Equations
Approach 1: FRP bars do not contribute.	
CSA -S806-12 [14]	$P_{pred} = \propto_1 f_c'(A_g - A_f)$; $\propto_1 = 0.85$
Approach 2: FRP bars' contribution based on decreased compressive strength	
Tobbi et al. [5]	$P_{pred} = \propto_1 f_c'(A_g - A_f) + \propto_f f_{fu} A_f$; $\propto_1 = 0.85$ & $\propto_f = 0.35$

Afifi et al. [11]	$P_{pred} = \propto_1 f_c'(A_g - A_f) + \propto_f f_{fu} A_f$; $\propto_1 = 0.85$ & $\propto_f = 0.25$
Approach 3: FRP bars' contribution depending on the ultimate concrete strains	
Hadhood et al. [7]	$P_{pred} = \propto_1 f_c'(A_g - A_f) + 0.003 E_{ft} A_f$
Xue et al. [16]	$P_{pred} = \propto_1 f_c' A_g + 0.002 E_{ft} A_f$; $\propto_1 = 0.85$

Tensile strength and tensile modulus of elasticity must be determined in order to utilize Approaches 2 and 3 in calculating the contribution of BFRP bars; so, a tensile test was performed on the bars. Table 4 presents the findings.

The predicted load-carrying capacities are found to be in good agreement with the experimental results as depicted in Table 5 and illustrated in Figure 5. The prediction based on the approach by CSA-S806-12 [14] underestimated the capacity since it neglects the contribution of FRP bars which reaffirmed the need to consider the contribution made by FRP reinforcement in compression. It was found that the design equation by Afifi et al. predicted the capacities better than other models. However, there is a significant amount of overestimation in B20 which, as discussed above, shows a discrepancy due to the possibility of compromised compressive strength.

Table 4: BFRP bar mechanical characteristics

S. N.	Diameter of reinforcement bar (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
1	10	1001.07	60.51
2	14	789.55	46.93
3	20	733.80	57.45

Table 5: Predicted load-carrying capacities of BFRP RC columns normalized to experimental capacities

Specimen ID	P_{pred}/P_{exp}				
	CSA-S806-12 [14]	**Tobbi et al.** [5]	**Afifi et al.** [11]	**Hadhood et al.** [7]	**Xue et al.** [16]
B10	0.85	0.93	1.01	0.95	0.94
B14	0.79	0.90	1.02	0.95	0.92
B20	0.80	1.08	1.24	1.25	1.13

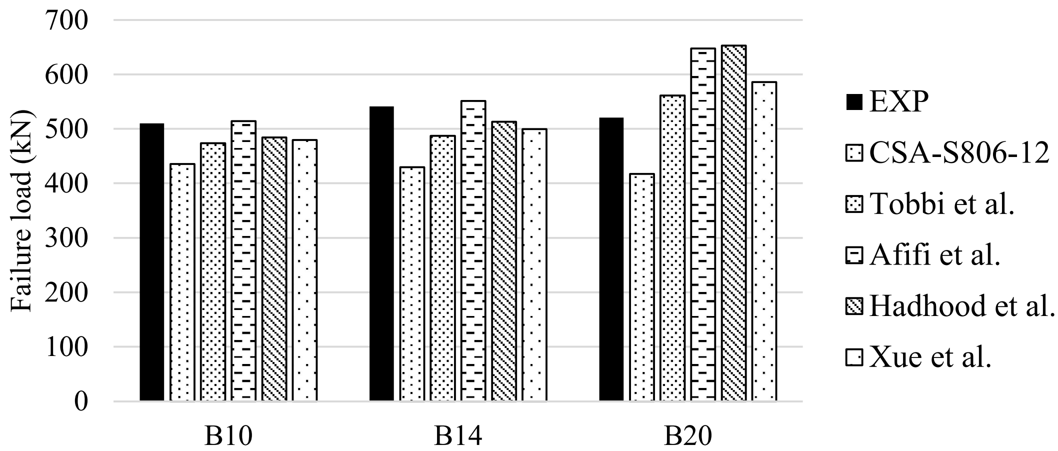


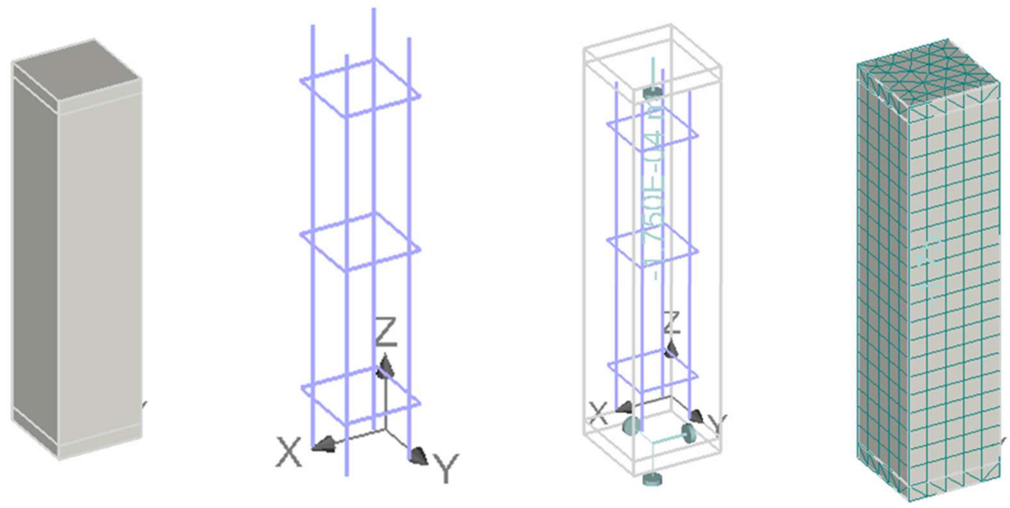
Figure 5: Comparison between predicted and experimental load-carrying capacities of BFRP RC columns

5. NUMERICAL INVESTIGATION

Tested specimens longitudinally reinforced with BFRP bars were numerically simulated on ATENA 3D. There are a total of three microelements that include the concrete specimen along with the top and bottom steel plate. The reinforcement cage is modeled as truss elements and a perfect connection is implied between concrete and the reinforcement. On the top steel plate, prescribed deformation is applied and on the bottom steel plate support condition is established. While meshing, tetrahedral elements are used for steel plates, and brick elements are used for the specimen. The optimum mesh size is found to be 30 mm. Details of the finite element models are given in Figure 6.

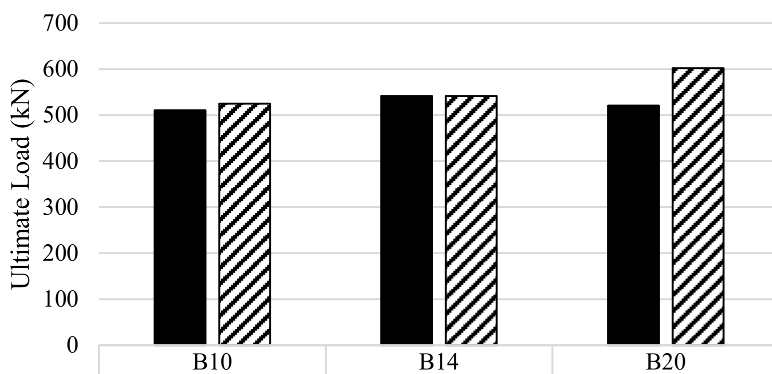
The Fracture-Plastic constitutive model is employed in this numerical analysis for concrete. It combines constitutive modes for both tensile and compressive behavior. This model can be used to simulate fracture closure due to crushing in different material directions, crushing under severe confinement, and cracking in concrete.

The experimentally observed ultimate loads and numerically computed loads are found to be in good agreement with slight overestimation as shown in Figure 7. The overall difference between experimental and numerical results is 7%.



(a) macro-elements (b) Reinforcement cage (c) Boundary conditions (d) Meshed specimen

Figure 6 Details of FE model



	B10	B14	B20
■ EXP	510.08	541.5	521
◪ FEM	525	541.3	602.1

Figure 7: Comparison between experimental and numerical results

6. CONCLUSION

The following conclusions have been formed based on the findings:

1. The contribution of BFRP to the load bearing capacity of a column under concentric loading is considerable, but less than that of steel bars, which increases with reinforcement ratio.
2. The findings demonstrate that the design equations established to assess the load-carrying capacity of columns reinforced with CFRP/GFRP bars may also be used to BFRP. It is

observed that the Afifi et al. [11] design equation predicted the load carrying capacity of columns better than other models.

3. There is a good degree of agreement between the numerical results and the experimental results.

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