International Journal of Scientific & Engineering Research Volume 12, Issue 1, January-2021 657
ISSN 2229-5518

Experimental Study on Steel-FRP Reinforced Concrete Beams with Large Rectangular Openings

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Abstract— This paper investigates the structural performance of concrete beams reinforced with steel and fiber-reinforced polymer (FRP) bars that having large rectangular openings. An experimental study was conducted on three FRP steel reinforced concrete (FSRC) beams using basalt FRP (BFRP) bars. The FSRC beams were consisted of one beam without openings served as a reference beam; one beam with non-reinforced openings and one beam with reinforced openings. All beams were tested under the effect of two line loads bending test up to failure. Based on the test results, it was found that the presence of opening produces earlier cracks at opening locations. These cracks increased and propagate continuously with the increasing in applied load and lead to earlier failure. Compared to similar beams without openings, the presence of non-reinforced and reinforced openings was found to produce reductions in strength of up to 75% and 63%, respectively.

Index Terms— Beams with openings, Basalt fiber-reinforced polymer, FRP, Stiffness, Ductility, Flexural strength, strengthening.
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1 Introduction

The elastoplastic characteristics of steel reinforcements have become important issues in steel reinforced concrete (SRC) structures located in harsh environments and/or active seismic zones. Fiber Reinforced Polymer (FRP) has become a practical alternative construction material replacing conventional steel reinforcements in reinforced concrete (RC) structures due to its advantages, such as, corrosion resistance, non-conductivity, high strength-to-weight ratio and light weight. Although FRP has many advantages to be adopted as a construction material, it intrinsically lacks some important structural characteristics (e.g. ductility and initial stiffness). Therefore, composite systems of steel and FRP rebar's to produce FRP steel reinforced concrete (FSRC) structures have been proposed in many experimental and analytical research programs found in the literature (e.g. **Ibrahim et al. 2015; Mustafa and Hassan 2018; Aiello and Ombres 2002**). Through these programs, it was reported that by adding FRP bars to the SRC structures the damage of structures due to steel corrosion can be mitigated. Moreover, the seismic resistance can be improved through controlling both the post yield stiffness and post-earthquake recoverability; that is the life safety objectives of RC structures can be achieved.

In continuation of the causes of failure of RC structures, the presence of openings in the web of RC beams leads to many problems in the beam behavior such as reduction in the beam strength and stiffness, excessive cracking, and excessive deflection. Despite its great influence on the structural performance of RC beams, there is ever increasing need for providing holes and openings at to the beams to allow the continuity of ducts and pipes for sanitation, heating, ventilation, air-conditioning, electricity, telephone and computer networks and other mechanical equipment. In fact, passing these ducts through transverse openings in the floor beam may be considered the most practical alternative arrangement instead of placing them underneath the soffit of the beam which needs covering them by a suspended ceiling, thus creating a "dead space" in each floor. In cases of small buildings, the saving thus achieved may not be significant compared to the overall cost but in cases of multistory buildings, any saving in story height multiplied by the number of stories can represent a substantial saving in total height, length of air-conditioning and electrical ducts, plumbing risers, and overall load on the foundation.

During the last few decades, several experimental and analytical studies have been conducted to investigate the mechanical properties of SRC beams with openings. Two main categories of studies have been carried out in this area: the first one has been conducted with the aim of finding the main parameters affecting the structural performance of such beams (e.g**. Mansur et al. 2001; Al-Shaarbaf et al. 2007; Ashour and Rishi 2000; Aykac et al. 2013; Herrera et al. 2017**), while the aim of the second category was directed to finding different ways for enhancing the performance of the beams and mitigating the influence of providing the openings on the strength and serviceability of the beams (e.g. **Nie et al. 2018; Osman et al. 2017; Elsanadedy et al. 2019; Maaddawy and Sherif 2009**). In this direction, providing additional reinforcements around the opening has been emphasized as a very good way to restore the strength and stiffness of the beam. The main reason for this is reported by many researchers due to counteracting the negative effects of the stress concentrations around the openings and preventing the premature failure of the beam.

To this end, although many studies have been found in the literature on the performance of FSRC beams without openings and SRC beams with openings, there are no enough data or design guidelines for FSRC beams with openings. Therefore, the objective of this study is to understand the structural behavior of FSRC simple beams with strengthened and non-strengthened openings through experimental investigations.

2 Experimental Program

The used cement was Portland Cement type CEM I – 42.5N complies with the **Egyptian Standard for Specifications, ESS:4756-1/2009**. The properties of used cement in this study are shown in **Table 1**. Crushed stone from natural sources with a nominal maximum size of 20 mm was used in this experimental work and was complied with **ESS:1109/2002**. The physical properties are presented in **Table 2**. Fine aggregate which was used in this work is a natural siliceous clean sand. Testing of sand was carried out according to the Egyptian standard specifications **ESS:1109/2002**. The physical properties of the sand are shown in **Tables 3**. Clean tap drinking water was used in this work. It was clean and free from impurities. **Table 4**. Show the mechanical properties of steel bars and was complied with **ESS:262/2015**. The stated materials were used as the basic solid ingredients in concrete mix.

Table 1: Physical and Mechanical Properties of Cement

Property		Results	Specifications Limits
Compressive Strength (N/mm²)	2 days	22.7	Not less than 10 N/mm²
	7 days	33.9	-
Soundness (mm)		4	Not more than 10 mm
Fineness of Cement (cm²/gram)		3190	-
specific gravity		3.15	-
Setting Time (minutes)	Initial	170	Not less than 60 Minutes
	Final	220	-

Table 2: Physical Properties of Coarse Aggregate

Property	Results	Acceptable Limit
Specific gravity	2.63	-
Unit Weight (t/m³)	1.62	-
Materials Finer than Sieve no 200	1.88	Less than 3%
Absorption %	2.03	Less than 2.5%
Abrasion (Los Anglos)	16.64	Less than 30%
Crushing Value	19.85	Less than 30%
Impact	11.30	Less than 45%

Table 3: Physical Properties of Fine Aggregate

Test	Results	Acceptable Limit
Specific Gravity	2.67	-
Unit Weight (t/m³)	1.73	-
Materials Finer than No. 200	1.68	Less than 3%

Table 4: Mechanical Properties of Steel

Properties	Measured Values		Minimum Specification Limit (ESS: 262/2015)		
	High Grade Steel B400B-R - Y10mm	Mild Steel B240B-P - R8mm	High Grade Steel B400B-R	Mild Steel B240B-P	Grade 60
Yield /Proof Stress	539 N/mm²	377 N/mm²	400 N/mm²	240 N/mm²	420 N/mm²
R_m/R_eH	1.21	1.24	1.08	1.08	-
% of Elongation	21.8%	28.3%	14%	20%	9%

Three reinforced concrete beams with a rectangular cross-section of 150 mm width, 300 mm depth and an overall span of 2000 mm were tested under two line loads bending test to meet the objective of this research. The specimens were designed to investigate the strength and serviceability of RC beam reinforced with a combination of steel and BFRP bars (Hybrid) as a main reinforcement. A detailed description of the test specimens follows and is supported by **Table 5** and **Figure 1**:

- Specimen **BSF** served as a reference specimen for the FSRC beams. In this beam, the longitudinal reinforcement consisted of two 10-mm-diameter steel bars and one BFRP bar, and the transverse reinforcement consisted of 8-mm-diameter internal closed stirrups spaced every 150 mm.
- Specimen **BSFO** served as an FSRC beam with non-reinforced openings where it was reinforced with the same reinforcement as specimen BSF and provided with two large rectangular openings of 150 mm height and 250 mm length located at 250 mm from each support. The stirrups above and below the openings were closed to the heights of the top and bottom chords.
- Specimen **BSFO-IF** served as an FSRC beam with reinforced openings where it was the same as the beam BSFO but was provided with two 10-mm-diameter BFRP bars parallel to all openings' edges.

Table 5: Details of tested beams

Specimen number	Bottom Bars		Top Steel Bars	Steel Stirrups	Opening BFRP Reinforcement
	Steel	BFRP			
BSF	2Φ10	1Φ10	2Φ10	Φ8@150 mm	-
BSFO	2Φ10	1Φ10	2Φ10	Φ8@150 mm	-
BSFO-IF	2Φ10	1Φ10	2Φ10	Φ8@150 mm	8Φ10

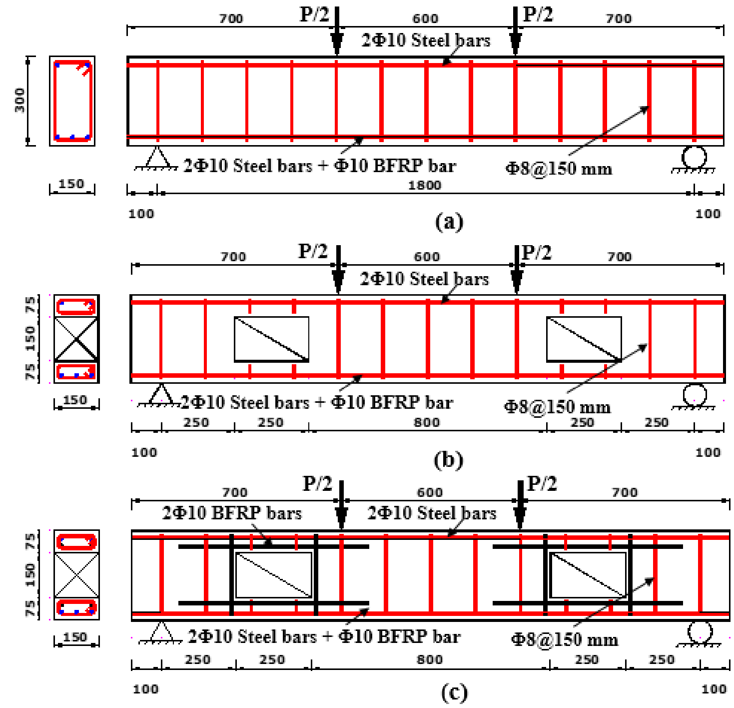

Figure 1: Details of the tested beams (dimensions are in mm): (a) BSF; (b) BSFO; (c) BSFO-IF

A target compressive strength of 35 MPa was applied to all tested beams and **Table 6**. shows the ingredients proportions. The mechanical properties of BFRP bars were presented as shown in **Table 7**. It's worth to be mentioned that, the tensile strengths of the BFRP bars were defined based on the cross-sectional area of each bar and based on the manufacturer, the basalt fiber content was 60% of the cross-sectional area.

Table 6: Proportion of concrete mixture

F_{cu} (MPa)	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (liter/m³)
35	450	608.7	1126	202

Table 7: Mechanical properties of BFRP bars

Material type	Elastic modulus *E* (GPa)	Yield stress f_y (MPa)	Tensile strength f_u (MPa)
10-mm-diameter BFRP bars	48.1	-------	1113

A linear variable differential transformer (LVDT) was used during testing to record the deflection at mid-span of the tested beams. The axial strain histories for both the steel and FRP reinforcements were recorded during the test by using 5-

ISSN 2229-5518

mm-long strain gauges. While, electrical strain gauges with 50 mm length were used to measure strain in the compressive zone of the concrete.

All beams were tested when their age being more than 28 days. The load was applied at the two third points of the span of the tested beam using a rigid steel rod. The initial reading of the dial gauge was first recorded. The load was applied in increments of about 5 KN. The load was maintained constant between two successive increments for about 2 minutes, to enable recording of the different reading, and observing the initiated cracks.

3 Experimental Results and Discussion

Table 8 summarizes the characteristic values of these curves and together with the observed failure mode of each specimen. The terms P_{cr} and δ_{cr} represent the cracking load and its corresponding mid-span deflection, respectively, and they were approximately defined from the first turning points of the load-deflection curves. The terms Pu and δ_u represent the peak (ultimate) load and its corresponding displacement, respectively. Values of the displacement ductility factor, μ_u, at the ultimate load (i.e., $\mu_u = \delta_{cr} / \delta_u$) were also calculated for each beam specimen.

Table 8: Test results for the tested beams

Beam No.	P_{cr} KN	P_u KN	δ_{cr} (mm)	δ_u (mm)	μ_D (δ_u / δ_{cr})	Mode of failure
BSF	35	149	1.5	42	25	Compression
BSFO	12	38	1.1	16	14	Shear at opening
BSFO-IF	20	64	1.35	13	10	Shear at opening

It was observed from **Figure 2** which shows the load versus mid-span deflection curves for the tested beams that, the solid beam (BSF) showed the well-known structural behavior of hybrid steel-FRP RC beams in which the behavior is characterized by high initial stiffness up to the first cracking at mid-span followed by lower stiffness up to steel yielding. Before the yielding of the steel bars, the observed behavior of the beam was slightly affected by the contribution of the FRP reinforcement. This could be because of the small contribution of the FRP bars to both the beam strength and deformation. Beyond the yielding of the steel bars, the contribution of the FRP reinforcement became significant and controllable, where a hardening zone with a clear positive post yield stiffness was realized up to failure. At failure, excessive deep cracks and crushing were appeared at the bottom and top mid-span fibers of the beam, respectively.

The beam with non-reinforced openings (beam BSFO) showed a very less stiffness, strength, and ductility comparing with the solid beam. According to the test results, a sharp reduction of about 75% of the ultimate load was happened when the beam was provided with the two openings. Moreover, the existing of the openings led to a reduction in the ductility to about 40%. The reason behind that reduction is that the existing orthogonal corners of the openings caused more stress concentration at these corners that lead to early undesirable cracks above and below the openings. As the load increased, these cracks widened and propagated upward and new cracks were created around the openings and the formed cracks propagated towards the point of load application.

By reinforcing the openings with cross BFRP bars parallel to the openings as in beam BSFO-IF, the beam could restore some of its stiffness and strength. In this beam, the strength was about one and half that of the beam with non-reinforced openings. The reason behind that is the contribution of the opening reinforcement in delaying and decreasing the cracks at the openings' corners.

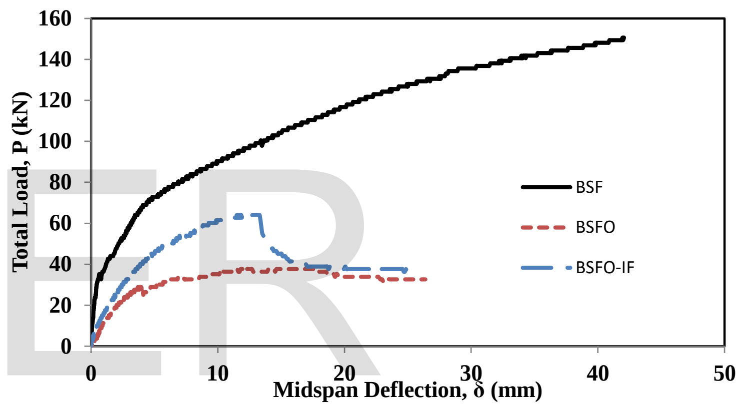

Figure 2: Load mid-span deflection curves of the test beams

Cracks appeared at the bottom of control beam BSF as usual, the flexural failure took place due to huge propagation of middle bottom cracks. For beams with opening, cracks started around the opening and at the middle bottom of tested beams. Cracks in tested beam BSFO was superior in comparison to beam **BSFO-IF** because this beam strengthened with additional reinforcement around openings. Moreover, the crack patterns of the tested beams are shown in **Figure 3**.

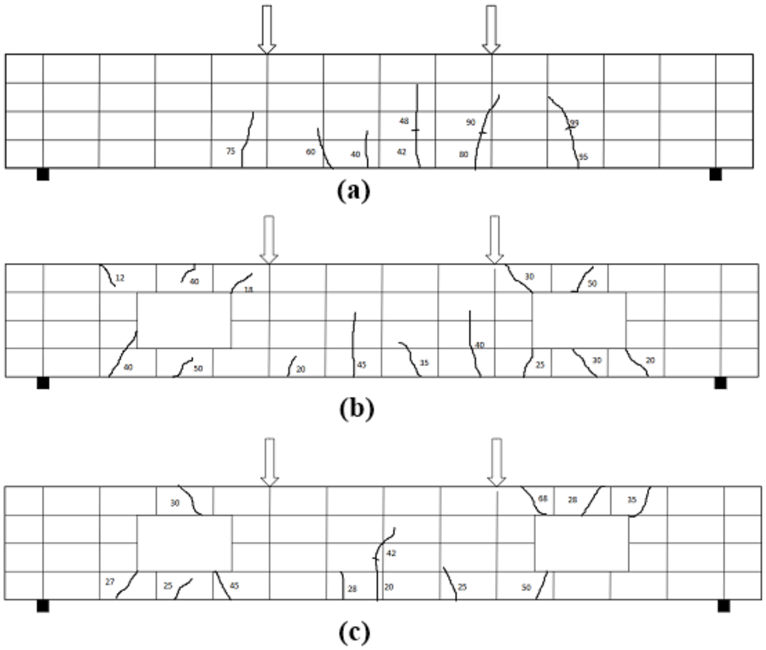

Figure 3: Pattern of cracks of the tested beams: (a) BSF; (b) BSFO; (c) BSFO-IF

4 Conclusions

In this study, an experimental study to investigate the structural behavior of FSRC beams with non-reinforced and reinforced openings was conducted. The experimental investigations of this study showed that, the provision of openings to FSRC beams causes great reduction in the stiffness, strength, and ductility of the beam. By strengthening the openings with BFRP bars, the stiffness and strength increased with significantly positive results, Also, the appearance and propagation of cracks above and below the openings delays and the presence of BFRP bars around holes interlocked the spreads of cracks.

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