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Rehabilitation of Hybrid RC-I Beams with Openings Using CFRP Sheets

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Abstract

This research presents an experimental investigation of the rehabilitation efficiency of the damaged hybrid reinforced concrete beams with openings in the shear region. The study investigates the difference in retrofitting ability of hybrid beams compared to traditional beams and the effect of two openings compared with one opening equalized to two holes in the area. Five RC beams classified into two groups, A and B, were primarily tested to full-failure under two-point loads. The first group (A) contained beams with normal weight concrete. The second group (hybrid) included beams with lightweight concrete for web and bottom flange, whereas the top flange was made from normal concrete. Two types of openings were considered in this study, rectangular, with dimensions of 100×200 mm, and two square openings with a side dimension of 100 mm. A full wrapping configuration system for the shear region (failure zone) was adopted in this research. Based on the test results, the repaired beams managed to recover their load carrying capacity, stiffness, and structural performance in different degrees. The normal concrete beam regains its total capacity for all types of openings, while the hybrid beams gain 84% of their strength. The strength of hybrid concrete members compared with normal concrete is 81 and 88% for beams of one opening and two openings, respectively.

Keywords: CFRP; Hybrid Concrete Beam; Openings in Shear Zone; Rehabilitation of Beams.

1. Introduction

Precast concrete elements are widely used to increase the speed of construction, and these elements comprise beams, slabs, and columns. Currently, the world is developing a new type of concrete using green technology to limit pollution and construction costs. Lightweight Concrete (LWC) is an eco-friendly material with a low density that reduces construction costs by decreasing the dead load. Several lightweight aggregates are currently available with a wide range of properties. The sources of these lightweight aggregates might be either natural sources like tuff, diatomite, scoria, and pumice or artificial sources of industrial by-products permeable constituents such as slag, vermiculite, slate, and expanded clay. On the other hand, lightweight concrete is generally considered a weak material that cannot carry the different loads applied to the structures. Therefore, the designers moved towered using layered concrete beams (hybrid beams) to withstand shear and forces. In hybrid systems, high-strength concrete can withstand compressive force at the top zone of the beam, while LWC offers the advantage of being lightweight at the rest of the section. Many researchers studied the behavior of conventional hybrid beams consisting of two types of concrete and achieved promising results [1-4].

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One of the early lightweight aggregates that are used frequently in construction is pumice. The various discharged smokes of the cooling magma develop tiny deep voids during volcanic activation that produce the current porous arrangement of the pumice. Many researchers have shown that lightweight pumice concrete could be categorized as structural concrete with specific treatments. These studies have discussed lightweight concrete's mixed proportions and characteristics that varied according to the origin of the aggregate used [5-8].

Including the web openings in the reinforced concrete beams (RC) is regularly required to facilitate the required essential services of heating ducts, air conditioning systems, electrical conduits, and water supply, especially when no additional height is permitted. As a result of the sudden change in the cross-sectional dimensions of the beam, the opening corners are subject to high-stress concentration, which can lead to excessive cracking, which is considered inappropriate for reliability and an aesthetic viewpoint. Many researchers addressed the effect of cracks around the holes in the concrete beams [9-13]. Cracks indicate the total extent of the damage due to a high level of loading condition, and they could be a sign of severe problems with a higher degree. Their effect depends on the use of the structure and the nature of such cracks. In this sequence, Jomaa'h and Gaiden [14] examined the strength, ductility, and energy absorption of layered concrete beams with a different arrangement of openings. The use of two-layered concrete beams (LWC with thermostone in the web and bottom flange of I-beam section) resulted in lower ultimate loads and a stiffer load-deflection response about (9.3-48.8%) compared with the reference beams, whereas the ultimate load of three-layered concrete beams (LWC with thermostone in the web of the I-beam section) is decreased about (25.6-58.1%). Introducing openings of dimension (100×1000) mm reduces the energy absorption capacity of the RC I-section beams by at least 80% compared to solid beams, while the beam with opening size (100×100) mm decreases by up to 16%.

Rehabilitation of deteriorated concrete to achieve its original strength is an effective way to reduce the cost of dismantling concrete structures and construction of new elements instead of old ones. Moreover, effective repairing processes should be applied to prevent further cracks initiation and handle the reasons that cause damages [15].

There are many techniques for the strengthening of any existing structure with certain merits and demerits; one of the emerging methods is the use of Fiber Reinforced Polymer (FRP) composite. In the last decade, FRP composite materials have experienced a continuous increase in structural strengthening and repairing applications worldwide. Furthermore, when comparing the FRP composite to steel materials, it was found to provide unique opportunities to develop the shapes and facilitate their use in construction [16]. Numerous studies [17-23] have been taken place to study the performance of using FRP composites as strengthening materials in concrete beams with openings and the results showed that FRP composites have increased significantly the collapse load. Fayyadh and Abdul Razak [24] presented the findings of an analytical and experimental investigation on the efficiency of Carbon Fiber Reinforced Polymer (CFRP) strips in the restoration of RC beams with varying levels of pre-repair damage severity. It emphasizes the impact of repairing damaged beams with CFRP sheets on load capacity, steel strain, mid-span deflection, and failure mechanisms. The primary outcomes of the research are that repairing the beams with CFRP sheets externally bonded enhances loads carrying capacity while reducing the mid-span deflection and steel strain. In addition, at the post-repair stages, a more significant pre-repair damage level results in a higher deflection and steel strain. Ahmed et al. [25] studied the repair effectiveness of CFRP and steel plates in the concrete beams with openings. The researchers focused on plate thickness as a key parameter. The results show that increasing the thickness of steel plates has a limited effect on the maximum load capacity. The CFRP sheet is more effective than steel plate in increasing the load capacity of beams. Also, the research conducted on the same subject shows that the rectangular configuration of CFRP sheets is better than the hexagonal one [26].

In addition, Abed et al. (2020) [27] conducted an experimental assessment of the Performance and failure mode of CFRP-repaired RC beams as a function of web opening diameter. The findings indicate that the behavior of CFRP repaired beams changed from brittle to ductile during the repair process. The failure mode of CFRP repaired beams with a smaller opening diameter moved from shear to flexural failure, whereas the failure mode of CFRP repaired beams with a larger opening diameter was controlled by CFRP debonding at the shear zone. Yu et al. [28] carried out an experimental study on the shear capacity of pre-cracked reinforced concrete (RC) beams shear strengthened with CFRP strips. The failure mode, shear capacity, load-deflection curve, and moment-curvature relationship of strengthened specimens are investigated using CFRP strips spacing, shear span ratio, and pre-cracked degree. This study observed three failure modes of CFRP strips-strengthened RC beams: interfacial adhesion failure, debonding failure, and fracture failure of CFRP strips. Also, the upgraded degree of shear capacity of specimen's increases gradually with the decrease of CFRP strips spacing. Furthermore, Yu et al. (2021) [29] presented a study on diagonal crack width assessment of shear-strengthened pre-damaged beams with CFRP strips. The main conclusion was that the diagonal crack width of the shear-strengthened high pre-damaged beam is 40% higher than that of the shear-strengthened undamaged beam.

For all the previous researches that carried out on the behavior of hybrid RC members strengthened by different techniques, limited studies have focused on applying FRP composite for repairing damaged hybrid reinforced concrete beams with openings. The main objective of this work focuses on examining the effectiveness of repairing process using CFRP sheets and recovering the load capacity of pre-damaged beams with different opening shapes.

2. Experimental Program

2.1. Beam Descriptions

To conduct this experiment, as shown in Figure 1, two group of RC beams with openings were tested, see Table 1 and Figures 2. The geometry of all the beams was identical, h= 240 mm, b_w= 80 mm, t_f= 40 mm, and b_f= 180 mm. The total length was 1600 mm, and the effective span was limited to 1500 mm, while the effective depth was 210 mm. The beams were designed in such way to fail by shear, accordingly, the shear behavior can be investigated through the test. The main tensile steel reinforcement consisted of 2-Ø12 mm deformed steel rebar. Additionally, 2-Ø8 mm rebar have been used in compression zone. Stirrups with a diameter of 6 mm have been spaced at 100 mm c/c along the entire beam for the shear reinforcement. To prevent premature failure, 4-Ø6 mm diagonal bars were used around the openings [30]. As shown in the schematic diagram Figure 2, two shapes of openings were considered, rectangular with dimensions of 100 mm × 200 mm and two square openings with a side of 100 mm for each one and with clear space of 50mm between openings. The opening depth to total depth ratio was fixed and equal 0.42, which represent the boundaries between small and large holes [31]. All the beams were tested previously up to the failure, where the cracks are well recognized through the beams especially around the opening. All the beams were repaired by injecting the cracks with epoxy and strengthened with a CFRP sheet in the shear zone. The beams were retested under two-points loading in a simply supported condition.

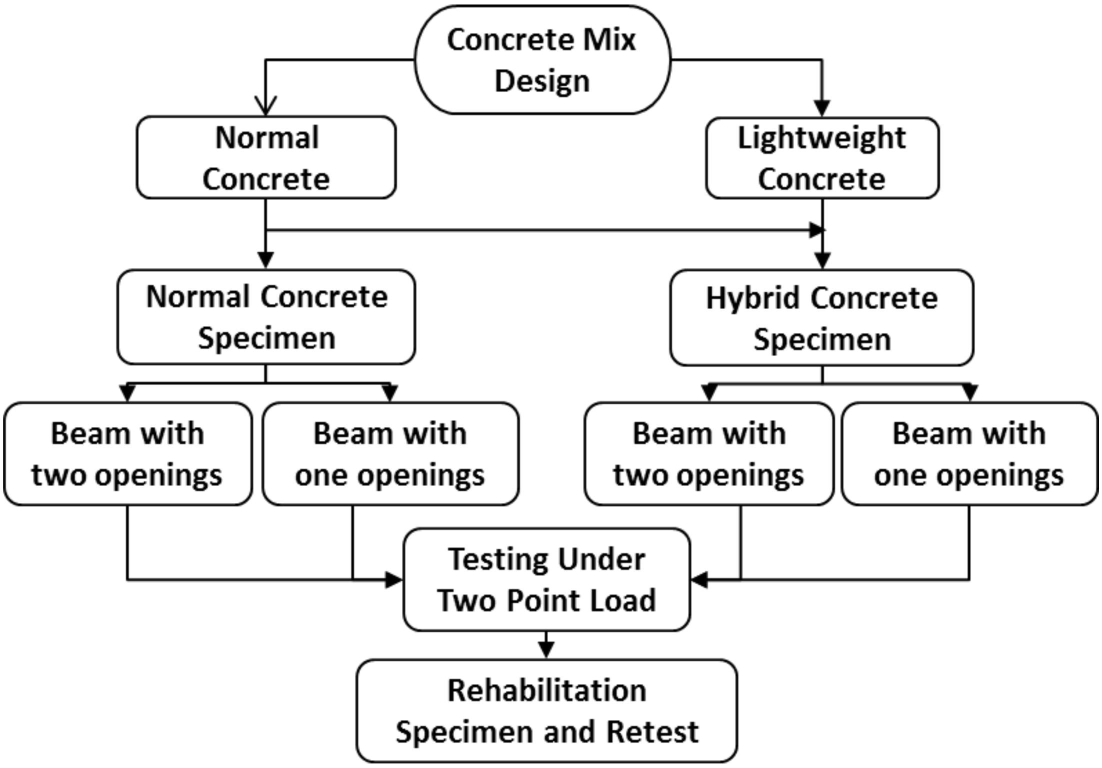
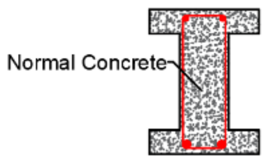
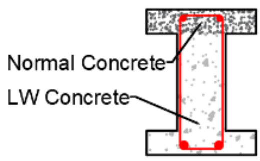
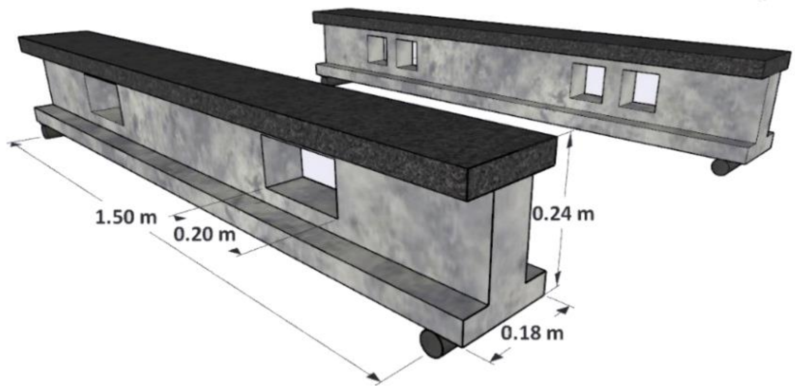


Figure 1. Flow Chart of Experimental Work Program

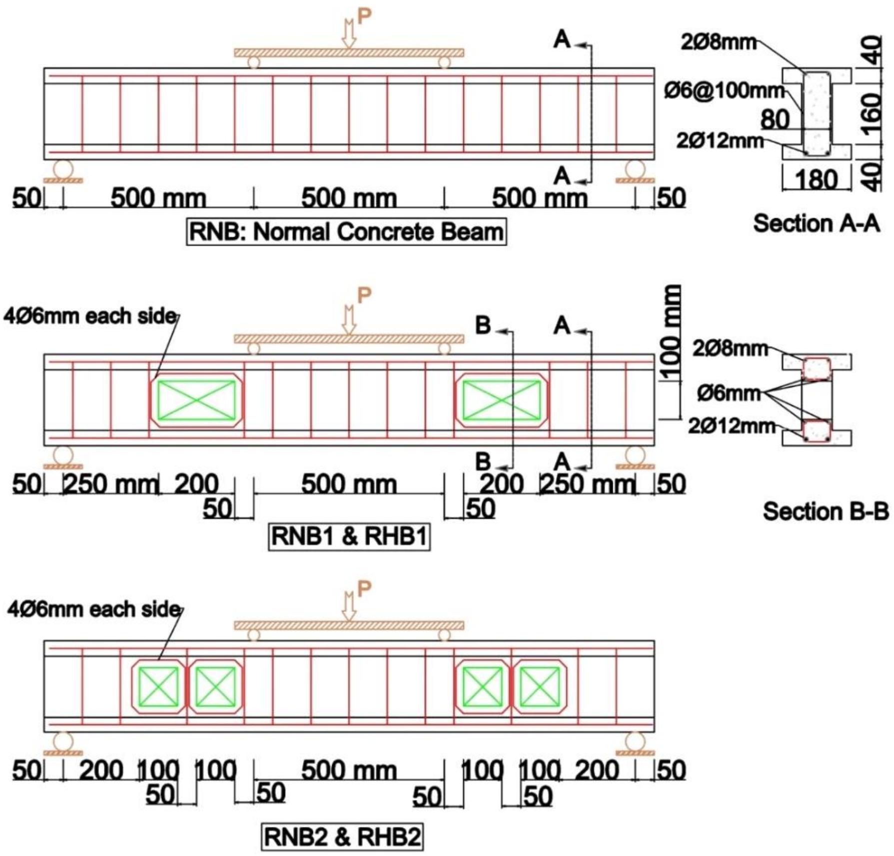
Table 1. Details of specimens

Group	Specimen	Description	
Control	RNB	Normal concrete	
A	RNB1		
	RNB2		
B	RHB1	Hybrid concrete	
	RHB2		

R: Repaired, N: normal, B: beam, H: Hybrid, 1: one opening, 2: two openings



a) Three-dimension shape of specimen



b) Schematic diagram for reinforcement details of specimen (all dimensions are in mm)

Figure 2. Specimen and its schematic diagram

2.2. Materials

In this study, Type I Portland cement, fine aggregate (4.75 mm), and coarse aggregate passing sieve No.12.5 were utilized in the construction of the concrete. The concrete mix proportions were 1:1.7:2:0.39 (cement: fine aggregate: coarse aggregate: water). Grade 420 deformed bars were used as tensile reinforcement. Grade 300 deformed bars were used for shear reinforcement. Tables 2 and 3 illustrate the Grading of Fine Aggregate and coarse aggregate, respectively.

Table 2. Grading of Fine Aggregate

Sieve size (mm)	Cumulative passing %	Limit of IQS No. 45/1984 for Zone No. (1)[32]
4.75	90.2	90– 100
2.36	63.5	60– 95
1.18	47.9	30– 70
0.60	29.8	15– 34
0.30	7.6	5– 20
0.15	1	0– 10

Table 3. Grading of coarse Aggregate

Sieve size (mm)	Cumulative passing %	Limit of Iraqi specification No. 45/1984 [32]
14	97.55	90-100
10	74.8	50-85
5	6.05	0-10

To achieve lightweight concrete, local coarse natural lightweight aggregate (pumice) was used. It is available in the north of IRAQ, where it is used to produce light buildings units. The stone was crushed by a crushing machine. The maximum aggregate size was 12.5 mm, which was replaced with normal coarse aggregate in the volumetric ratio of 50% for each batch. Pumice was sieved to the grading which is presented in Table 4 while Table 5 shows the general properties of pumice. Due to the pumice cellular structure, lightweight aggregate absorbs more water than the normal-weight aggregate. In the hot weather, to prevent the continuous absorption of pumice, which caused fast workability losses, the aggregate was immersed in the water for 24 hours, to attain saturation. Then, the water was dripped off and the aggregate spreads within the testing laboratory for twenty-four hours to let the aggregate particles reach the condition of the saturated surface dry.

Table 1. Pumice aggregate grading

Sieve size (mm)	Passing (cumulative) %	Limits of ASTM C330 [33]
12.5	98	90-100
9.5	70.45	40-80
4.75	1	0-20

Table 2. Properties of pumice

Properties	Specification	Results	Limits
Specific gravity	ASTM C127 [34]	1.59	-
Absorption %	ASTM C127	28	-
Dry loose unit weight, kg/m3	ASTMC29/C29 [35]	575	-
Sulfate content (as SO3) %	Iraqi specification [32]	0.1	≤ 1

2.3. Mechanical Properties of Concrete

At the age of 28 days, a series of tests were performed to assess the compressive, splitting tensile strength, and modulus of rupture of Normal concrete (NC) and Lightweight concrete (LWC). The cylinders (150×300 mm) and prisms (100×100×500 mm) were tested to estimate the compressive and splitting tensile strength as well as modulus of rupture using a universal machine in the structures laboratory, College of Engineering, Kirkuk University with an ultimate load capacity of 3000 kN, results were reported and presented in Table 6.

Table 3. Properties of hardened concrete

Type of concrete	Curing period	Density (kg/m^3)	$f_c^{'}$ (MPa)	f_{ct} (MPa)	f_r (MPa)
NC	7 days	2373	33	4.3	5.8
	28 days		34	4.4	7.6
LWC	7 days	2000	22	3.5	4.6
	28days		27	3.7	5.1

2.4. Repairing Procedure

The unidirectional Carbon Fiber Reinforced Polymer (CFRP) type (DCP-Profiber CW 230) was utilized in the present work for the rehabilitation of the reinforced concrete beams. Before wrapping the damaged beams with a CFRP sheet, the beam surface was brushed and cleaned to ensure an appropriate surface preparation for bonding. Strong coat primer was used as a base layer that provides a sound surface for the sheets, besides, it can be used for injecting the present main open cracks in the beams. Strong coat primer can be described as a two-element epoxy resin with ultra-soft viscosity that is largely used in injecting structural concrete buildings. Once both elements are mixed, the mixture was applied using a brush in a quantity of approximately (0.25 to 0.30 kg/m^2) as required in the product's technical sheets depending on the roughness of the substrate. After 24 hours, DCP-Pro Fiber CW 230 sheet was placed in the correct direction into the (Quickmast ER350) resin and carefully apply the pressure on the sheet with a spatula.

The CFRP sheet is very thin with a thickness of 0.131 mm, and it has a tensile strength of 4.9 GPa and a modulus of elasticity of 230 GPa with an extreme elongation of 2.1%. Debonding failure of FRP strengthening RC beams usually takes place via areas of high stress concentrations.

Debonding is usually associated with FRP material closure with the existence of cracks that appear in the concrete substrate, and this leads to a significant reduction in the progression of enhancing the strength that can be achieved using the FRP with expected brittle failures [36]. To avoid these types of failures, steel angles with dimensions of 38×38×2 mm were applied at the corner using 2 flat-head screws, 4mm in diameter and 35mm in length. These bolts were anchored at concrete through a plastic sleeve at areas of high-stress concentrations, as shown in Figure 3, to provide an adequate bond between CFRP and concrete.

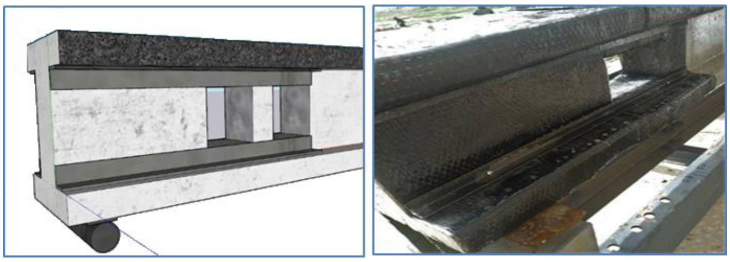


Figure 1. Repairing the damaged Beams

2.5. Test Setup

All the prepared samples were tested using a two-point loading frame with a capacity of 300 kN, the configuration as shown in Figure 2. The load progression has been done in small increments using a hydraulic jack controlled manually at the required precision, where the data have been recorded every 3 kN load increments. The Mid-span deflection was recorded by a mechanical dial gauge of 0.01 mm accuracy. The spacing of the two-point load was 500 mm while the shear span was 500 mm for each side, and the total effective span was 1500 mm. To prevent knife-edge failure over supports, small pieces of steel plate of 40 mm in width and 4 mm in-thick were used to distribute the concentrated load, as shown in Figure 3. For any loading increment, both applied load and mid-span deflection was recorded using manual measurements. The cracks were identified using a thick black marker at the failure, and a digital camera has photographed the beam specimens.

3. Results and Discussion

3.1. Loads and Modes of Failure

The experimental work consisted of five tested beams, which were classified into two groups, A and B, in addition to one reference concrete beam. Group A consists of a normal weight concrete beam, whereas B consists of hybrid concrete beams. It is worth mentioning that all the beams were tested till failure. The cracks were initiated in the members, as shown in Figure 4, and load-deflection curves were recorded for all specimens. In this stage, the control solid beam (NB) was failed in shear-flexure while the other four beams had a shear failure in their openings, as presented in Figure 5. The experimental test results in terms of the influence of CFRP sheets on restoring load capacity of the damaged beams, failure loads, and mid-span deflection have been summarized in Table 7. In this table, P_u and P_{ur} refer to the original and repaired beams' ultimate strengths, respectively, whereas δ_u and δ_{ur} refer to maximum mid-span deflection at the first and second tests, respectively. In addition, regarding Table 7 and Figure 4, the results of the beams in the first testing series were denoted as NB, NB1, NB2, HB1, and HB2, respectively. After repairing these beams, the capital letter R was added to the used symbol for the beams to distinct the second test results. It is essential to say that deflection of retrofitting members was started at zero, assuming that real-life damaged structures are jacking up before the repairing process started.

Table 4. Test results and failure modes

Group	Specimen	Damaged Beams			Specimen	Repaired Beams			P_{ur}/P_u
		P_u (kN)	δ_u (mm)	Mode of failure		P_u (kN)	δ_u (mm)	Mode of failure	
Control	NB	95	12.7	shear-flexural	RNB	115	16.8	Shear Flexure	1.21
A	NB1	81.8	11.4	shear	RNB1	84	8.1	Shear + debond	1.03
	NB2	70.7	8.1	shear	RNB2	60	9.0	Shear + debond	0.84
B	HB1	66.3	9.6	shear	RHB1	65	11.2	Shear + debond	0.98
	HB2	61.9	7.6	shear	RHB2	52.6	8.0	Shear + debond	0.84

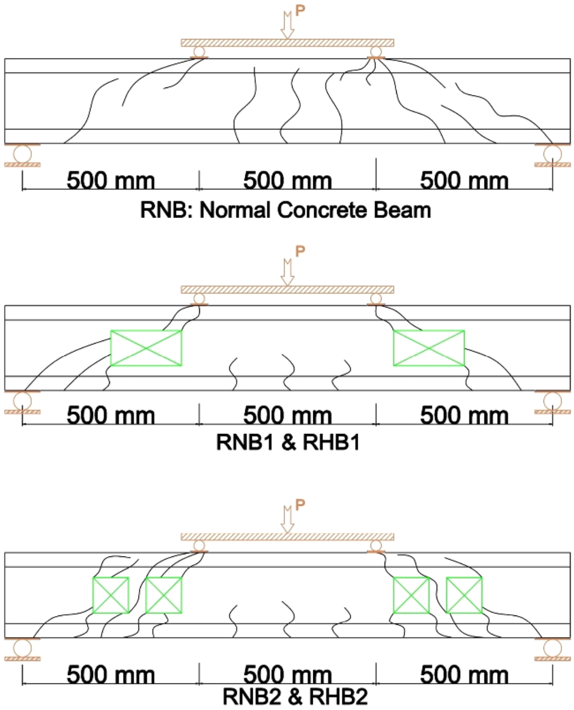


Figure 4. Typical failure mode observed for original beams

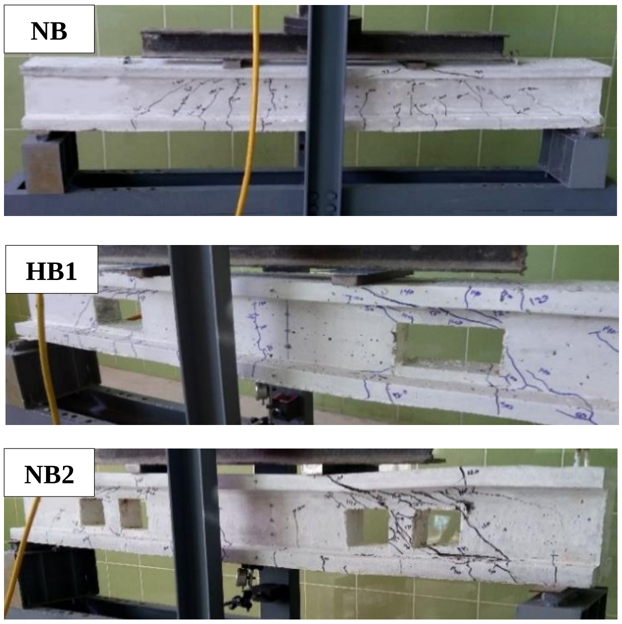


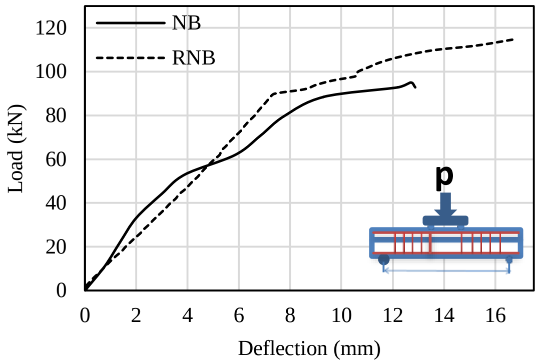
Figure 5. Mode of failure of the damaged specimens prior to strengthening

For group B in Table 7, the hybrid RC beams (HB1 and HB2) were repaired by CFRP sheet beams (RHB1 and RHB2). In the beginning, the results show that the capacity of the hybrid concrete beams with one and two openings compared with the similar normal concrete specimens are 81% and 88%, respectively. This reduction can be clarified as the holes were in the mid-depth of the beams in the region of lightweight concrete, where the concrete strength, f'_c = 27 MPa, is less than normal concrete, f'_c= 34 MPa. As presented in Table 6. Shear capacity of any concrete member is proportioned with the square root of concrete strength, and for this case, the ratio was 89% which is very close to tested values. The CFRP sheets in the strengthening configuration managed to re-gain the beam strength approximately by 98% and 84%, respectively. Obviously, in the two test groups, almost the same behavior pattern was obtained despite the different results, where the member with one rectangular hole can gain almost its strength compared to the beam with two square openings. At failure load, the widening of diagonal cracks at the corners of opening with the initiation of new flexural crack width has collapsed the members, besides the anchorage bolts started to take off from their positions due to high vertical tension force of the sheets (shear forces), as shown in Figure 6.

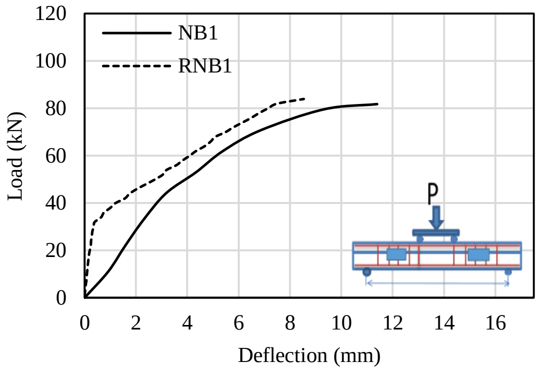
Figure 6. Typical failure mode observed for repaired beams

3.2. Stiffness of Repaired Beams

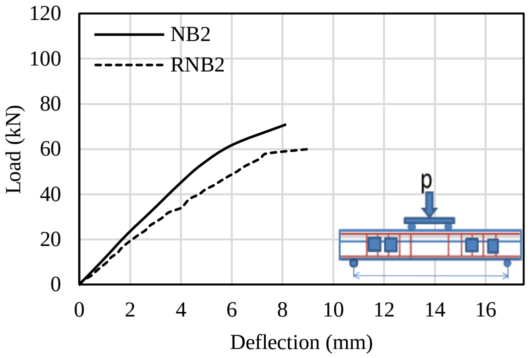
It can be observed from the load-displacement behavior in Figure 7 that the contribution of CFRP sheets to the specimen strength varies depending on opening shape, number, and dimensions. Regarding these variables, two concepts should be clarified here. The first one, when the beams are tested at the beginning, crack took place at all the body of the member in different intensity, and they reduced the stiffness of the member to a significant degree. The second concept identifies that the CFRP sheet and its binding epoxy are brittle materials in origin and have large tension strength. The presence of slight pre-cracks has a minor effect on the stiffness of CFRP strengthened beams, while severe damages affect the shear capacity of the RC beams [28]. Using FRP sheets with a primer coat and epoxy provides the specimens high initial stiffness; as it can be concluded from Figure 7, RNB and RNB1 exhibited significantly higher initial stiffness with less mid-span deflection at peak load compared to the original specimens of the beams that are in good agreement with the outcomes of the literature [37]. In addition, damage levels in normal concrete beams were less than in hybrid beams. The exception for the RNB2 specimen, which showed a decrease in stiffness when retested, was due to the damage level in this specific beam (the wide cracks are located at the line joining the points of the opening corners). The slightly lower stiffness of the beams of group B, shown in Figure 7 is primarily due to the same mentioned reasons above, where the cracks were more severed for the lightweight concrete in the shear zone, which leaves a permanent effect on the beams.



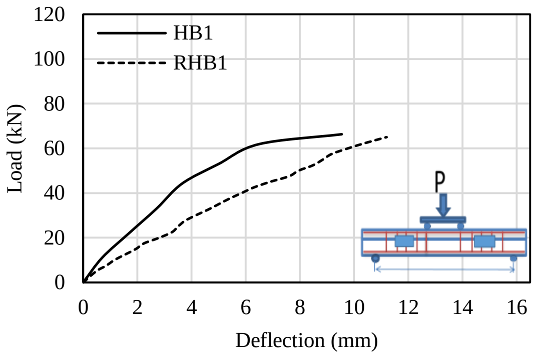
a) Load-Deflection of normal concrete beam



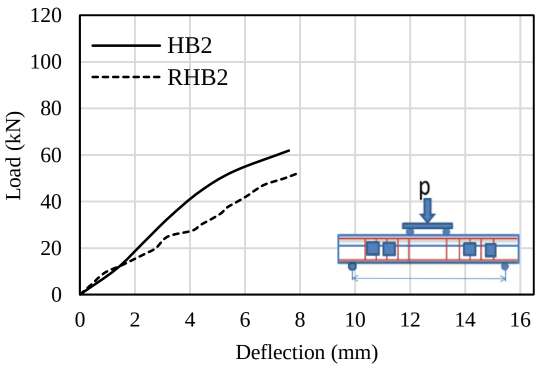
b) Load-Deflection of NC beam with one opening



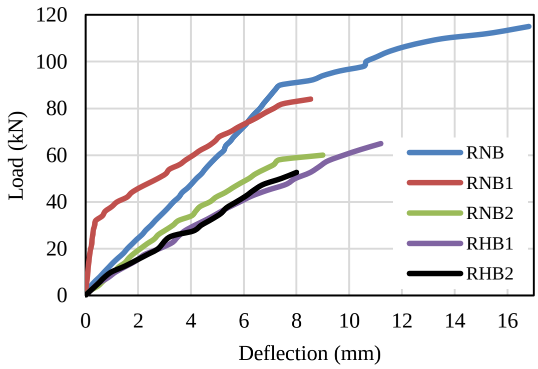
c) Load-Deflection of NC beam with two openings



d) Load-Deflection of HC beam with one opening



e) Load-Deflection of HC beam with two openings



f) Load-deflection of Repaired beams

Figure 7. Load-deflection relation of original and repaired beams

3.3. Evaluation of Performance

Due to the characteristics of the stress-strain shape of FRP materials, it is logical, from the engineering standpoint of view, to evaluate the deformability and strength factors to assess the performance factor as an overall factor. Both deformability and strength factors are the two most critical factors related to two serious phases in the design procedure that affected the behavioral features of the designed structural members. These two phases are the ultimate and serviceability limits that are evaluated at the stage of the concrete compressive strain, and tensile steel rebars strain at the end of its linear behavior. The process of determining the deformability factor has been evaluated by dividing the limits of ultimate deflection to the serviceability deflection.

The ratio of the ultimate load to the serviceability load is the strength factor. The product of both deformability and strength factors is defined as the performance factor. The performance factor (PF) is known as the global factor since it integrates both the strength and deformability where both of them are weighted evenly. The designers should pay attention to these two factors to obtain the best structural strength and performance where such factors require precious optimization. Alternatively, the key concept for PF permits the designer to equally assess the strength and deformability constraints for a certain application such as seismic design. The PF highlights the essential requirements for both strength and deformability as the materials and design parameters are chosen [38].

For a damaged reinforced concrete beam, repaired with the CFRP sheet, both deformability and strength factors can be associated with the serviceability and the failure load limit states for any structural element. The failure load and serviceability limit states can be defined, in this case, as the failure load and the corresponding deflection of damaged reinforced concrete beams [39]. The definitions of both deformability and strength factors are given below:

$$\mathrm{DF} = \frac{\delta_{ur}}{\delta_u} \tag{1}$$

$$\mathrm{SF} = \frac{P_{ur}}{P_u} \tag{2}$$

where (δ_u and δ_{ur}) and (P_u and P_{ur}) are the deflections and loads at the failure limit state for the repaired and damaged beams, respectively. Consequently, the general structural functioning for the repaired composite beams is measured using a factor known as performance factor (PF) to combine the strength and deformability. The PF is known as:

$$\mathrm{PF} = \mathrm{DF} \times \mathrm{SF} \tag{3}$$

For various repaired beams, different structural performance factors such as PF, SF, and DF were calculated using Equations 1 to 3. As shown in Figure 8, RNB attained the maximum performance factor, followed in sequence by RNB1, RNB2, RHB1, and RHB2 at about 1.60, 0.77, 0.94, 1.15, and 0.89, respectively. The investigation of the values for the performance factors verifies that the level of the damages in the original specimens and design details of the repaired structural element powerfully affect the ductility of the reinforced concrete beams restored with FRP systems.

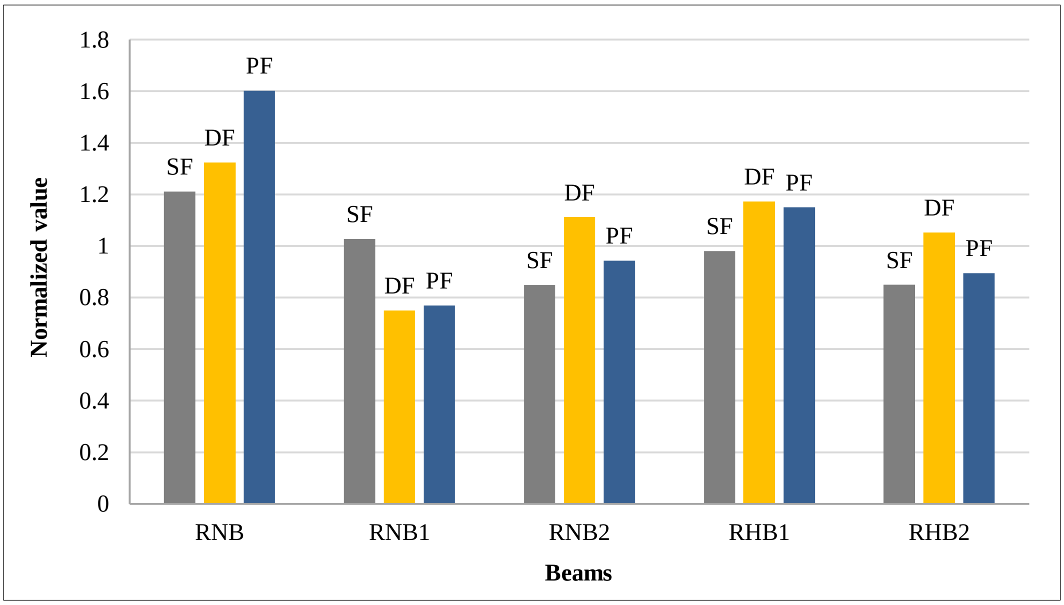


Figure 8. Structural performance factors

4. Conclusions

Based on the examination of the performed experimental tests of the repair RC beams with openings, the following conclusions can be drawn:

- The results of tested members show that damaged hybrid members could be repaired in a very effective manner using CFRP sheets, especially if the opening size is less than 200 mm [27]. A lot of time and effort used for demolishing and reconstruction of new members can be saved.
- The repaired controlled beam NBR achieved an increase in its primary strength by 21%, and it fails by flexural. The tests proved that a damaged beam that shows flexural failure mode could be rehabilitated more effectively than beams that show shear failure mode.

- Using concrete beams with one large opening is more effective than using two square openings with the same area for both normal and lightweight concrete beams.
- The whole primary strength of concrete beams was achieved using one hole, while only 84% of the original strength was recovered for the beams with two holes.
- The strength of hybrid concrete compared with normal concrete is 81% and 88% for beams of one and two openings, respectively.
- Cracks mode in the repaired damaged beam specimens at the end of the experimental test was very close to the corresponding original samples.
- The size of pre-existing damage considerably influenced the effectiveness of FRP fabrics as a repairing material in shear-deficient beams. The repaired beams achieved less performance by about (13–38%), as with the undamaged ones.
- The quadrilateral reinforcing of holes in the reinforced concrete beam has a significant effect on the regain strength of a repaired beam, preventing rapid progression of cracks in the original beams and allowing for ductile behavior after retrofitting [30].

5. Nomenclatures

CFRP	Carbon Fiber Reinforced Polymers	DF	Deformability Factor
FRP	Fiber Reinforced Polymer	HC	Hybrid Concrete
LWC	Lightweight Concrete	NC	Normal Concrete
PF	Performance Factor	RC	Reinforced Concrete
SF	Strength Factor		

6. Declarations

6.1. Author Contributions

Methodology, A.S., M.J. and D.G.; investigation, A.S., M.J. and D.G.; writing—original draft preparation, A.S. and D.G.; writing—review and editing, D.G. and N.O. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

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6.5. Conflicts of Interest

The authors declare no conflict of interest

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