Strengthening Strategies for RC Beams with Vertical Openings Using Embedded Steel Bars

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ABSTRACT

Circular or rectangular openings are often incorporated into Reinforced Concrete (RC) beams to accommodate the service requirements of the buildings, such as telephone lines, sewage systems, and water supply pipes. These concrete beams need to be strengthened and repaired, as the presence of openings reduces their stiffness, which results in severe deformations and a significant redistribution of load. An experimental study of the impact of vertical openings on the structural behavior of simply supported RC beams is presented in this research. Five RC beams were tested as part of the experiment. The beams were split into two groups based on the vertical opening's shape. One of the beams was kept as a reference beam (without any openings). One beam in each group was internally strengthened with reinforcing steel rebar, whereas the other was not. The experimental findings demonstrated that, for all studied specimens, independent of the opening shape, the development of openings within the RC beams resulted in an increase in the service midspan deflection and a decrease in the ultimate load carrying capacity. The maximum decrease in the ultimate load was approximately 27.7% for the un-strengthened specimens compared to the reference specimen. In contrast, compared to the beams without reinforcement, the rebar strengthening was successful in enhancing the ultimate load and reducing the service midspan deflection by approximately 19% and 29%, respectively. Additionally, the experimental results demonstrated that, when compared to a reference beam, the strain values of the top and bottom steel reinforcement at the mid-span increased at the same applied load level (at service load). However, when additional steel reinforcement was used to strengthen the beam around the vertical openings, the strain in both the top and bottom rebar decreased.

Keywords-component; reinforced concrete beam; vertical opening; strengthening

I. INTRODUCTION

In building construction, the incorporation of openings in RC beams is often necessary to pass the mechanical and electrical services, such pipes, and ducts used the in air-conditioning, water supply, sewage, telephone lines, and gas lines, as shown in Figure 1. Therefore, regular openings are usually used in most of the floor beam structural elements. Based on the opening orientation, there are two common types of openings in RC beams: horizontal openings that cross the beams in the direction of their width, and vertical openings that cross the beams in the direction of their depth. The effect of these openings on the strength of the RC beams should be considered in the analysis and design [1]. The behavior of RC beams with transverse openings has been extensively studied and is well established. While, the effect of the vertical opening has not been sufficiently studied, various studies have assessed how different openings affect the performance of the RC beams numerically and with finite element methods [2-4]. Because of these openings, the sturdiness of the beam drops, higher deflection takes place, and the regular stress distribution is interrupted, resulting in the early formation of cracks. Different solutions have been proposed to address these issues. The presence of openings in the RC beams reduces their load-bearing capacity, stiffness, ductility, and energy dissipation ability. The corners of the openings are typically the weakest regions of the beams [5]. Also, the presence of openings creates a severe safety hazard and reduces the load carrying capacity of the elements.

There are many strengthening methods used to increase the capacity and resist stresses. Some of these methods use steel plates or Fiber Reinforced Polymers (FRP) as external reinforcement [6, 7]. Authors in [8] investigated the influence of incorporating openings in concrete beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. The study involved five beams with GFRP and openings in both vertical and horizontal directions, positioned in the flexural region. The key parameters examined included the orientation and quantity of the openings. The findings indicated that the vertical openings improved the strength of the beams, but they also increased the mid-span displacement by 39%, compared to the beams without openings. Additionally, substituting two adjacent openings with a single equivalent opening decreased the beam's strength.

Fig. 1. Various service pipes passing through RC beams in commercial buildings.

The current study highlights the importance of considering openings in the design of RC beams and explores the potential application of GFRP bars as reinforcement. In summary, the research demonstrates that the openings in concrete beams with GFRP reinforcement have a substantial impact on the overall performance by reducing the strength, increasing the mid-span displacement, and influencing the reinforcement strain [8]. Authors in [9] examined the behavior of seven RC beams measuring 1400 mm in length with a cross-section of 180 × 120 mm, under a bending load. All beams were designed to ensure the flexural failure (i.e., flexure-critical beams). The beams were subjected to two-point loads, 300 mm apart. The variables included the presence of openings, opening width, and the thickness of the strengthening steel tube. The results demonstrated that as the opening width increased, the deflection at mid-span increased and the ultimate load decreased. The ultimate load showed a decrease of 15.75%, 24.2%, and 32.5%, with a cross-section reduction of 17%, 33%, and 50%, respectively. In contrast, the improvement percentages for the beams reinforced with 1.5 mm thick steel plates were 11.78%, 12.14%, and 13.28% for the same respective opening widths. The strengthening method with steel pipes showed noticeable improvement for the specimens. Eleven simply supported RC deep beams with openings were experimentally tested in [10] under two-point static stress till failure. One of the test specimens was without any opening. The size, location, and shape of the vertical openings as well as the strengthening method were the primary variables in this investigation. It was found that the opening caused a 12%–19% reduction in shear strength, while the openings located in the constant-moment region resulted in an 8%–13% decrease. To counter these effects, the use of ultrahigh-performance concrete near the openings was proposed, which resulted in a 14% increase in the ultimate load capacity. Previous studies have examined the effects of transverse openings on the RC beams. However, limited research has been conducted on the impact of circular and rectangular vertical openings on the RC beams, despite minimal recommendations provided by the building codes. This gap is addressed in the present paper by investigating the behavior of RC beams with vertical openings and studying the effect of adding internal rebar to strengthen the openings in the RC beams.

II. EXPERIMENTAL PROGRAM

After having been reinforced with embedded steel reinforcement close to the opening, RC beams with rectangular and circular vertical openings were subjected to an experimental test program to examine their flexural response. Five RC beam prototypes with simple bracing were cast and tested with a symmetrical two-point load. Rebar was used to reinforce two of these beams. One of the beams was kept without opening, denoted as CRB.

A. Materials

All beam specimens in this study were casted with Ordinary Portland Cement (OPC) that was produced in Iraq. The chemical composition and physical properties of the cement were based on the Iraqi standard specification IQS. No.5/ 2019 [11] and ASTM-C150-21 [12]. Graded crushed gravel and natural sand with maximum sizes of 10 mm and 4.75 mm, respectively, were also used. The sand utilized for concrete making complied with the Iraqi Specification IQS/2 2016) [13] and ASTM C33/C33M-23 [14]. All steel rebars used in the experimental part of this study were deformed. The steel rebars were tested according to ASTM A615 / A615 M-20 [15]. The size of the steel bars, yield stress, and the ultimate strength are summarized in Table I. The modulus of elasticity is assumed to be 200000 MPa.

TABLE I. MECHANICAL PROPERTIES OF STEEL BAR

Nominal diameter (mm)	Measured diameter (mm)	Area, (mm^2)	Yield strength F_y (MPa)		Tensile strength F_u (MPa)	
			Test	ASTM-A615 (min.)	Test	ASTM-A615 (min.)
8	8.02	50.52	392	280	589	420
10	9.94	77.60	530	420	672	550
12	11.9	111.22	585	420	707	550

B. Concrete Mix Design

The process of designing the concrete mix, according to ACI 211.1 [16] included more than one attempts to find the appropriate weights and quantities to reach a concrete mix with a compressive strength standard cylinder of 30 MPa. This concrete mix consists of sand, gravel, cement, water, and some chemical additives. Table II shows the details of the concrete mix design for 1 m³ of concrete.

TABLE II. CONCRETE MIX DESIGN

Cement (kg)	Sand (kg)	Gravel (kg)	Water (L)	Superplasticizer (L)
380	850	1005	165	5.00

C. Specimens Details

The geometry of the openings and the efficiency of the rebar as reinforcement around the openings were examined in this study. Five RC beams, both with and without openings were casted and subsequently tested. Each beam has a rectangular cross section with a width of 200 mm, a depth of 250 mm, and a total length of 2300 mm. These beams were classified into two major groups, based on the space of their opening (circular or rectangular), ensuring the minimum depth requirement by ACI code (ACI 318M-19 code Article 9.3.1.1), which is (*L*/16) for the simply supported conditions.

TABLE III. CONCRETE MIX DESIGN

Groups	Beam	Size of opening (mm)	No. of opening	Opening location	Strengthening methods
I	CRB	No	No	No	Reference
	B1-C-C9-WS	Ø 50	9	Mid-span	No
	B1-C-C9-SR	Ø 50	9	Mid-span	Rebar(Ø1)
II	B2-C-S1-WS	294 × 60	1	Mid-span	No
	B2-C-S1-SR	294 × 60	1	Mid-span	Rebar(Ø1)

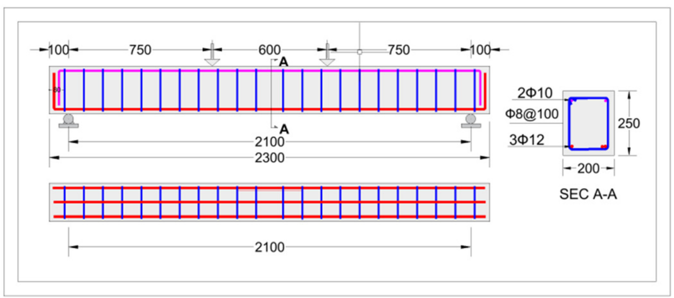
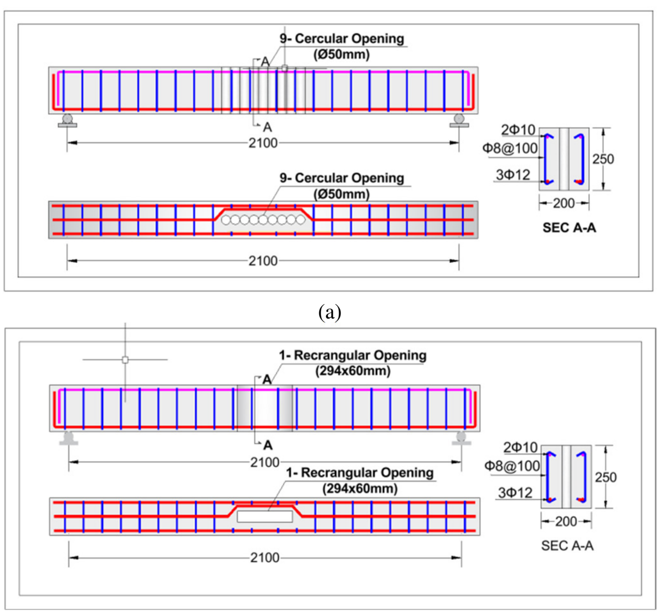


Fig. 2. Detailing/Details of reference beam.

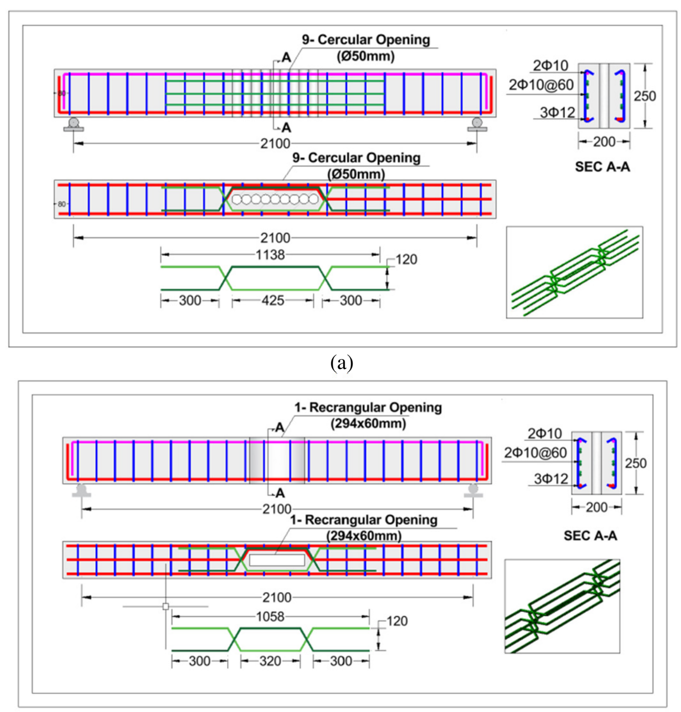


(a)

(b)

Fig. 3. Details of beams with openings: (a) B1-C-C9-WS, a beam with an unreinforced 50 mm circular opening; (b) B2-C-S1-WS, a beam with an unreinforced rectangular opening.

For the beams with nine openings, the holes were made using a PVC pipe of 50 mm diameter, while, for the beam with a single rectangular opening, a wooden box measuring 293 mm × 50 mm was used to create the hole. It is worth noting that, for the beams with nine adjacent openings, the total area of the openings is equivalent to that of a single rectangular opening. The flexural reinforcement consisted of three tensile bars with a diameter of 12 mm. In addition, two compression top bars with a diameter of 10 mm were provided in each beam. Transverse steel with a bar of 8 mm diameter was used as stirrup at a spacing of 100 mm. The vertical openings in the beams were strengthened with pre-fabricated embedded steel bars that consisted of three sets (2- Ø 10) as diagonal bars around the openings. The beam dimensions and other important details are illustrated in Figures 2-4 and Table III.



(a)

(b)

Fig. 4. Details of beams with strengthened openings: (a) B1-C-C9-SR, a beam with circular opening reinforced with rebar, (b) B2-C-S1-SR, a beam with rectangular opening reinforced with rebars.

D. Test Setup

Five beams were placed on the testing steel frame. All beams were simple supported and subjected to two-point loading, achieved using four steel saddles, as shown in Figure 5. The load was applied using a load cell with a hydraulic jack, and the response to the the applied loads were measured using a data logger. The applied load had been increased gradually at an increment of 5 kN. The cracks were marked on the beams for each load step after the appearance of the first crack. A single Linear Variable Differential Transformer (LVDT) was used to measure the mid-span deflection. Additionally, two electrical strain gauges were affixed at the outward surface of the longitudinal steel reinforcement: one strain gauge (S1) was attached to the mid-span section of the top bar Ø10 mm, and the other (S2) on the bottom bar Ø12 mm. This test was conducted in the Civil Engineering Laboratory at Baghdad University.

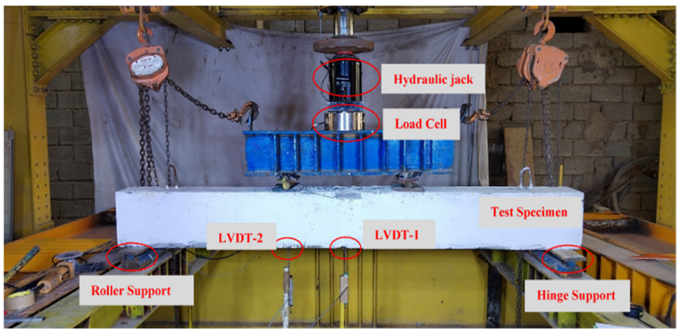


Fig. 5. Specimens under two-point load tests.

III. RESULTS AND DISCUSSION

This section presents the test findings from the beams, including the ultimate load, load–deflection and load–strain relationships, cracking, and failure behavior.

A. Ultimate Loads

The ultimate load capacity (P_u) for the flexural-critical beams is displayed in Table IV. The presence of the vertical opening reduces the load capacity of the beams, as portrayed in Figure 6. The reduction in the load capacity for beams B1-C-C9-WS and B1-C-S1-WS, compared to the reference beam's ultimate load, is 27.7% and 27.6%, respectively. Since the two specimens' total area of vertical openings was equal, the percentage of decline in the ultimate load was extremely close. These results are consistent with the findings of [6, 9]. It is important to note that this decline is due to a reduction in the concrete area needed to form the complete compressive stress block.

For beams B1-C-C9-SR and B2-C-S1-SR, the use of reinforcing steel as internal reinforcement around the opening delayed the failure and reduced the difference in the ultimate capacity to 13.7% and 16.5%, respectively, compared to CRB. The combined effect of increasing the beam's stiffness could be attributed to a greater load bearing capacity.

TABLE IV. ULTIMATE LOAD CAPACITY

Group	Beam	Ultimate load (kN)	Decrease in ultimate load (%)	Increment in ultimate load strength (%)
	CRB	112.3	Ref.	-
I	B1-C-C9-WS	81.2	27.7	Ref.
	B1-C-C9-SR	93.7	16.5	15.4
II	B2-C-S1-WS	81.3	27.6	Ref.
	B2-C-S1-SR	96.9	13.7	19.2

It is worth noting that, the presence of a steel reinforcement around the openings significantly increases the ultimate load capacity compared to the beams without strengthening in the same group. The improvements resulting from the rebar presence were 15.4%, and 19.2% for beams B1-C-C9-SR, and B2-C-S1-SR, respectively, as illustrated in Figure 6.

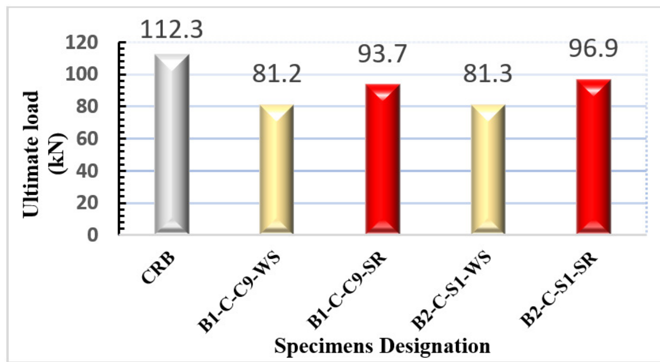


Fig. 6. Ultimate load for all specimens.

B. Load-Deflection Curves

Two loading stages were chosen to study the behavior of the beams with vertical openings: the service deflection at 65% of the ultimate load for the reference beam, and the ultimate load for the other beams.

Table V and Figures 7–8 demonstrate that the shape or number of openings had a significant effect on the behavior of the beams. Compared to CRB, beams B1-C-C9-WS and B2-C-S1-WS showed an increase in deflection of up to 23.13% and 25.68%, respectively, at the same applied load level (70 kN load stage). A decrease in the beam's moment of inertia could be the cause of the increase in deflection values; similar observations were reported in [6, 9].

Compared to the identical beam without strengthening, the use of steel reinforcement around the opening improved the deflection at the same applied load level in mid-span. Compared to the beams without strengthening in the same group (at the same service load level), the observed decrease in deflection for beams B2-C-C9-SR and B2-C-S1-SR was 29.79% and 19.92%, respectively.

TABLE V. BEAM DEFLECTION AT MIDSPAN

Group	Beam	At 70 kN load (service load for solid beam)			At ultimate load	
		Deflection (mm)	Increase in deflection (%)	Improvement in deflection strength (%)	Deflection (mm)	Variation in deflection (%)
	CRB	6.27	Ref.	-	12.32	Ref.
I	B1-C-C9-WS	7.72	23.13	Ref.	10.33	16.15
	B1-C-C9-SR	5.42	-13.56	29.79	10.52	14.61
II	B2-C-S1-WS	7.88	25.68	Ref.	10.64	13.64
	B2-C-S1-SR	6.31	0.64	19.92	11.18	9.25

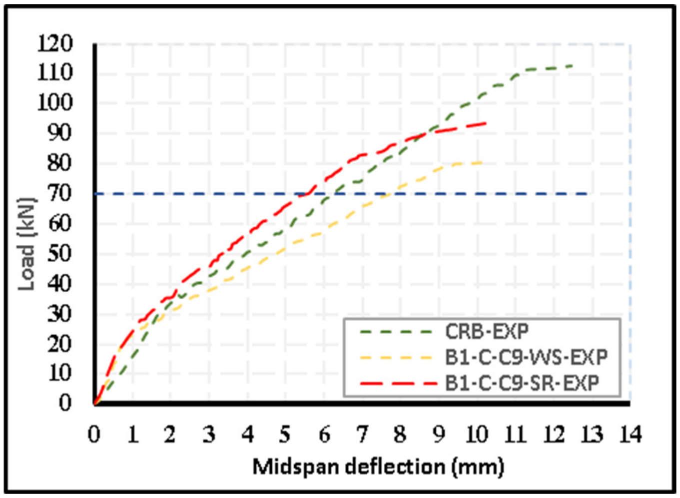


Fig. 7. Load mid-span deflection curves of Group I beams.

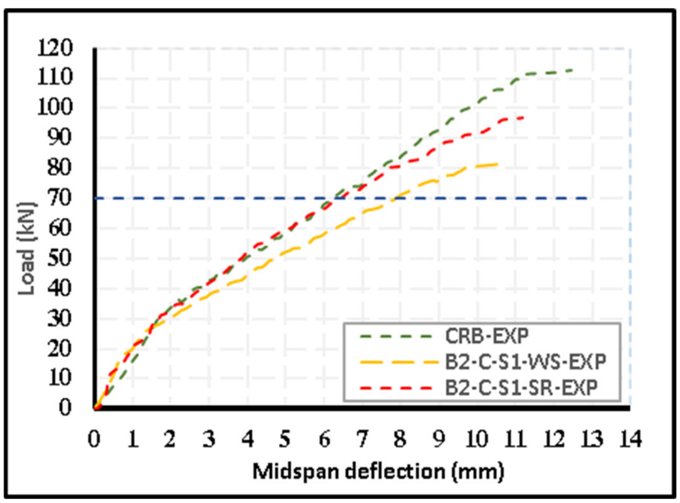


Fig. 8. Load mid-span deflection curves of Group II beams.

Additionally, a decrease in the mid-span deflection in beams with strengthened openings may indicate that the compression zone of the beams was strengthened by the enhanced reinforcement. The reinforcement helps distribute the stresses more evenly, reduces the risk of localized failure around the opening, increases the beam stiffness, reduces deflections, and improves the overall structural performance. Also, the additional reinforcement can help control the cracking in the vicinity of the opening and provides additional ductility to the beam.

C. Strain in Main Steel Reinforcement

Figures 9 and 10 depict the typical strains of the top and bottom reinforcement at each loading stage till failure. To examine the behavior of the beams, one loading stage was selected, and the strain was measured when the specimens reached service load at 70 kN, which was 65% of the ultimate load for the CRB.

The experimental results showed that the creation of a vertical opening increased the strain in top and bottom steel reinforcement at mid-span at the same applied load level. For example, at the 70 kN loading stage, the strain in the top rebar increased by 25.32% and 33.67%, and the strain in the bottom reinforcement increased by 40.45% and 36.06% for beams B1-C-C9-WS and B2-C-S1-WS, respectively, compared to CRB.

Figures 9 and 10 present the applied load-strain relationship in the bottom and top rebars for the beams with and without strengthened openings. The results indicate that the strain in both the top and bottom steel reinforcement decreased when strengthening was performed by adding more steel reinforcement around the vertical openings. For beam B1-C-C9-SR in Group I, the strain in the bottom rebars decreased by 31.49%. Compared to the un-strengthened beam, Group II showed a decrease of 29.55% for beam B2-C-S1-SR.

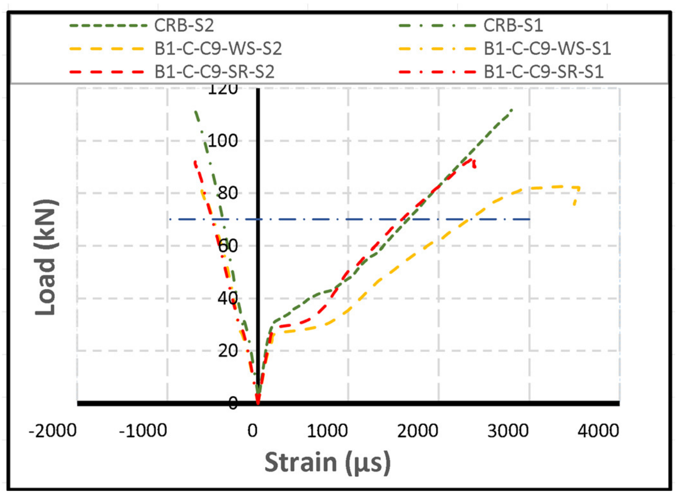


Fig. 9. Load-strain relationship in bottom and top main longitudinal bars in Group I.

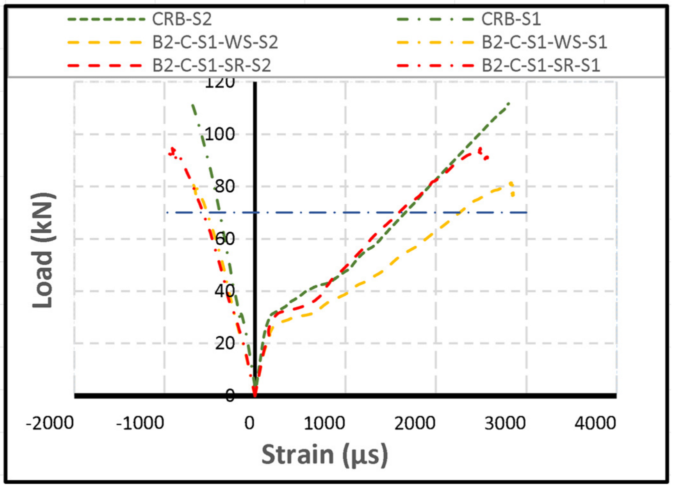


Fig. 10. Load-strain relationship in bottom and top main longitudinal bars in Group II.

D. Initial Cracks and Modes of Failure

Initial diagonal shear and flexural cracks were observed at the soffit of the tested beams, inclined at an angle 45° from internal or external support toward the loading plate. The locations and presence of openings had an effect on these cracks. Additionally, 45° cracks were observed at the opposite corners of the openings facing the loading location.

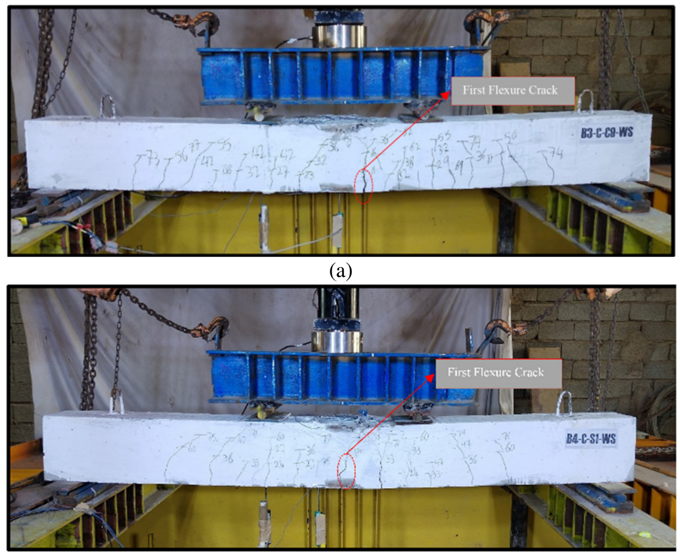
The first flexural cracks in beam CRB appeared at a load of 34 kN, or roughly 30% of the beam's failure load. The cracks widened and spread as a result of successive load increments. New diagonal shear cracks were also observed at the interior shear spans from the internal support in the direction of the applied load.

In contrast, the initial cracks for the beams with openings were located within the flexural zone, and the cracks appeared to be nearly identical. The initial cracking load for beams B1-C-C9-WS and B2-C-S1-WS was observed at 11 kN and 12 kN, respectively, corresponding to approximately 13.5% and 14.7% of their failure loads. Compared to the reference beam, it was found that the initial cracking load decreased by 67% and 65%, respectively. The flexural cracks that formed throughout the test were the cause of failure for these beams.

TABLE VI. FIRST CRACKING LOAD FOR BEAMS

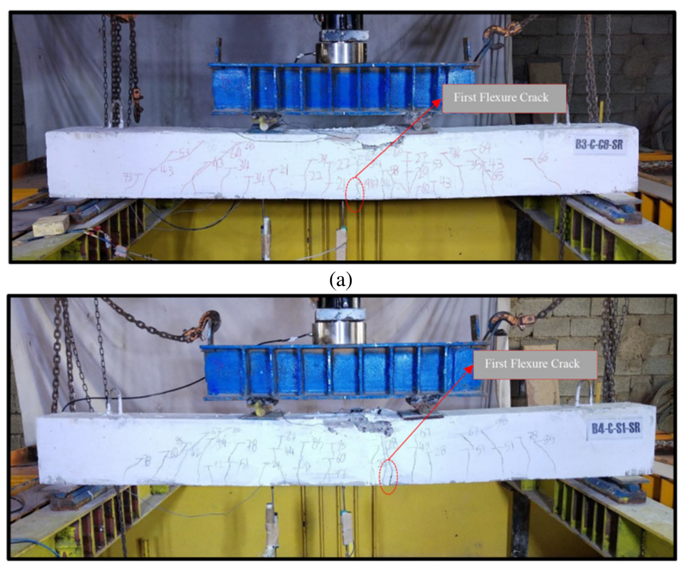
Group	Beam	First cracking load (kN)	Decrease in cracking load (%)	Improvement in crack strength (%)
	CRB	34	Ref	0
I	B1-C-C9-WS	11	67%	Ref
	B1-C-C9-SR	19	44%	72%
II	B2-C-S1-WS	12	65%	Ref
	B2-C-S1-SR	22	35%	83%

However, for the strengthened beams, the use of steel reinforcement around the openings delays the formation of the first diagonal and flexural cracks. Compared to CRB, the first cracking load for B1-C-C9-SR and B2-C-S1-SR dropped by 44% and 35%, respectively. The steel reinforcing around the vertical openings strengthens the beams and increases the initial crack strength, as shown in Table VI, and Figures 11, 12. For beams B1-C-C9-SR and B2-C-S1-SR, the first cracking load increased by 72% and 83%, respectively, compared to CRB. As there were openings in the flexural zone of the strengthened and un-strengthened beams, the flexural cracks developed before the shear cracks at the outer or interior shear spans. The loss of some concrete resulted in the formation of openings in the flexural zone, which decreased the flexural stiffness of the beams and made them less resistant to flexure, ultimately leading to an early failure. The crack pattern of the tested beams is displayed in Figures 11, 12.



(a) (b)

Fig. 11. Crack pattern for beams without strengthened openings: (a) B1-C-C9-WS specimen, (b) B2-C-S1-WS specimen.



(a) (b)

Fig. 12. Crack pattern for beams with strengthened openings: (a) B1-C-C9-SR specimen, (b) B2-C-S1-SR specimen.

IV. CONCLUSIONS

In this study, five simply supported Reinforced Concrete (RC) beams were tested under symmetrical two-point loading. One beam served as a reference beam without an opening (CRB), two beams were strengthened with additional steel reinforcement around the openings, and the remaining two had no additional reinforcement around the openings. Similar materials, size, and steel reinforcement were used to cast each beam. Based on the shape of the opening (rectangular or circular) and the number of openings (one or nine), these beams were divided into two major groups. The following are the conclusions drawn from the experimental study:

The first flexural cracking load decreased when an opening was present at the flexural zone. Compared to CRB, the initial cracking loads decreased by approximately 67% and 65% for the beams with one vertical opening and nine adjacent openings, respectively. The beams with additional reinforcement around the openings showed significant improvement in the first cracking strength. B1-C-C9-SR and B2-C-S1-SR exhibited an improvement of 72% and 83%, respectively.

The presence of beam openings significantly reduced the overall stiffness, which led to a reduction in the ultimate load capacity and an increase in the service mid-span deflection. A maximum reduction of 27.7% in the ultimate load capacity was observed for the beams with internal openings. However, for the same beam compared to CRB (at the same service load level), the maximum increase in deflection was approximately 25.7%.

When the RC beams were strengthened, their ultimate load capacities significantly increased, and the service midspan deflection decreased compared to the un-strengthened ones. For the beams with vertical openings, the maximum increase in the ultimate load and service deflection was approximately 19% and 29.8%, respectively. Compared to the un-strengthened beam in the same group, the strain in the bottom rebar decreased by 31.49% for B1-C-C9-SR and by 29.55% for B2-C-S1-SR, when strengthening was applied using steel reinforcement around the openings.

All RC beams tested in this study failed in flexural mode. The failure in the RC solid beam was characterized by a diagonal splitting along a load path, which is a line joining the outer edge of the load-bearing plate with the inner edge of the support bearing plate.

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