Strengthening Reinforced Concrete Beams Vertically Perforated through Their Entire Depth with the Use of Steel Tubes

Haider Abedulrudha Ghani
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
haidar.abd2101p@coeng.uobaghdad.edu.iq (corresponding author)

Amer F. Izzet
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
amer.f@coeng.uobaghdad.edu.iq

Received: 1 May 2025 | Revised: 11 June 2025 | Accepted: 15 June 2025

 DOI: https://doi.org/10.48084/etasr.11854

ABSTRACT

For architectural reasons, it is often necessary to place openings in reinforced concrete beams, even though these openings may compromise their structural integrity. The specific openings can be vertical and are intended to accommodate essential services, such as water and sewage pipes. Therefore, the former's effect must be carefully considered during the design of building structures to ensure their safety from collapse. The objectives of this study are to understand the effect of the vertical openings and to employ strengthening techniques. To fulfill these objectives, an experimental program was designed, which involved the casting of seven RC beams. These beams were tested as simply supported members under a symmetrically two-point applied load and were classified into four groups. These groups were divided based on the type of the vertical opening (shape, number, or strengthening techniques). Each group included two specimen types: non-strengthened reference specimens and specimens strengthened by steel tubes, in addition to the reference specimen that does not contain openings. The results indicated that the introduction of a vertical opening in the RC beam, without the application of any strengthening techniques, led to an increase in the mid-span deflection and a reduction in the ultimate load-bearing capacity when contrasted with the reference solid beam. It was found that when the opening was strengthened with a steel tube, the ultimate load increased and the mid-span deflection decreased compared to the specimens without strengthening in the same group. The presence of openings in the RC beams caused a decrease in their first flexural cracking loads. Moreover, using steel tubes to strengthen the vertical openings delayed the initial cracking compared with the unreinforced specimens.

Keywords-reinforced concrete beam; vertical opening; steel tube

I. INTRODUCTION

Vertical openings in beams are typically used to allow services to pass between the building floors through the beams to meet the architectural requirements as well as protect from damage, as seen in Figure 1. There are several types of openings. The vertical-circular openings are commonly used to extend the sewer and air conditioning pipes, while the vertical-rectangular openings are utilized to extend the bundles of the electrical wires or water supply pipes.

Beam damage occurs due to the vertical openings, and such openings inherently decrease the concrete area needed to fully develop the compressive stress block. This reduction in the concrete area can be considered in the beam design, as it leads to a decrease in the ultimate flexural and shear strength [1-3]. Additionally, the vertical openings also cut or obstruct the flexural and shear reinforcement bars. However, the latter should not be cut or damaged due to the openings at any location, unless permitted by a licensed design professional [4].

The positions, shapes, and reinforcement methods of these openings need to be carefully examined, as illustrated in Figure 1, since contractors sometimes install them randomly and incorrectly in the beams. The impact of the transverse openings in beams on their location, size, and shape has been the subject of experimental research [5-8]. Nevertheless, the impact of the vertical openings has not received much attention.

The shear behavior of RC T-beams with vertical openings at a different location on the flanges was examined [9]. It was shown that flange openings have a considerably lower shear capacity, ranging from 20% to 35% for beams with a single opening and from 17% to 40% for beams with two openings [9]. Authors in [10] found that the presence of vertical holes increased the shear strength of reinforced concrete beams by amplifying the diagonal tensile stresses, which leads to shear failure. The findings demonstrated that, to reduce the structural weaknesses in reinforced concrete beams caused by vertical pipe openings, proper reinforcement detailing and adherence to the design requirements should be considered [10].

Authors in [11] presented an experimental study of openings in RC beams with horizontal and vertical openings. They found that a vertical opening led to a reduction of approximately 6.6% in the ultimate load capacity. The circular openings had a much smaller effect than the square openings in the ductility index and ultimate load. Hence, the former were considered an ideal option for passing the services vertically through the buildings. In addition, it was found that when single-leg stirrups were applied at the opening area, they provided an effective response in compensating for the removed portion. However, for the transverse openings, the stirrups placed above and below the opening in each chord did not function properly. As a result, additional reinforcement around the opening was proposed to prevent premature failure.

Fig. 1. Incorrect extension of sewer pipes in a commercial building.

The behavior of RC beams with obstructed reinforcement bars has not been thoroughly examined. Therefore, this study experimentally investigated the behavior of the beam system and strengthening techniques using rebar and metal pipes under the effects of static loads.

II. EXPERIMENTAL PROGRAM

The objective of the experimental test program is to examine the flexural response of the RC beams with circular vertical openings after they are strengthened with steel tubes. Seven simply supported RC beams were cast and tested under symmetrical two-point loading. In addition to one specimen being cast without openings, three of these specimens were reinforced with steel tubes around the openings. Similar materials, measurements, and steel reinforcement were utilized to prepare each specimen.

A. Fine and Coarse Aggregate

For all specimens, the maximum size of natural sand used was 4.75 mm, along with graded crushed gravel with a maximum size of 10 mm, as per ASTM-C33-C33M-18 [13].

B. Reinforcement Bars

Deformed bars of 12 mm and 10 mm diameter were utilized as longitudinal reinforcement, while deformed steel bars of 8 mm diameter were used as closed stirrups. The tensile test was carried out on the steel reinforcement bar specimens to determine their tensile properties in accordance with ASTM A615/A615M-20 [12]. Table I shows the tensile properties of the steel bars.

TABLE I. MECHANICAL CHARACTERISTICS OF STEEL BARS

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	77.6	530	420	672	550
12	11.9	111.22	585	420	707	550

C. Steel Tubes

Steel tubes were used around the circular vertical openings to strengthen them. The outer diameters of the tubes were 75 mm and 50 mm, with a thickness of 3.6 mm and a total length of 250 mm. The yield strength was 301 MPa and 295 MPa for the tubes with diameters of 75 mm and 50 mm, respectively.

D. Concrete

For the experimental work, ordinary Portland cement was used. The compressive strength of the cube was determined by testing six cubes measuring 150 mm. The average compressive strength of concrete at 28 days was 30 MPa.

E. Details of Specimens

The overall length of all specimens was 2300 mm with the simple supports located at 100 mm from each end of the beam giving a clear span of 2100 mm. All specimens had the same cross-sectional dimensions, the beam width was 200 mm, and the total height of the beam was 250 mm. All specimens had the same flexural and shear reinforcement. The flexural reinforcement consisted of three tensile bars with a diameter of 12 mm as well as of two compression top bars with a diameter of 10 mm. Transverse steel with a bar of 8 mm diameter was used as stirrups at a spacing of 100 mm. The longitudinal and transverse reinforcement was designed according to ACI-318-19 [8], to ensure flexural failure and prevent any premature shear failure. The beam dimensions along with other details are illustrated in Figures 2-4. The total area of the vertical openings in a single specimen is 17,671 mm² for all specimens, in order to study the effect of the strengthening technique by comparing them with each other in different groups and with the reference specimen without openings. To more easily identify the description of each beam, all of them were given a designation representing their variable, and whether they were solid or with an opening. Figure 5 depicts the specimen naming convention.

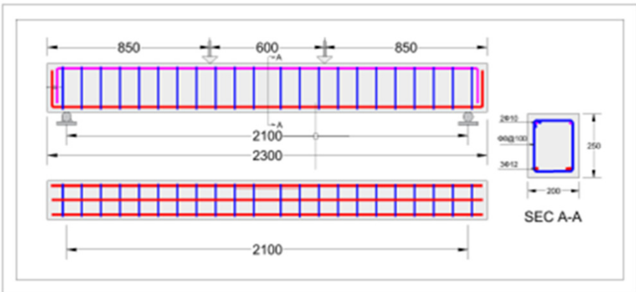
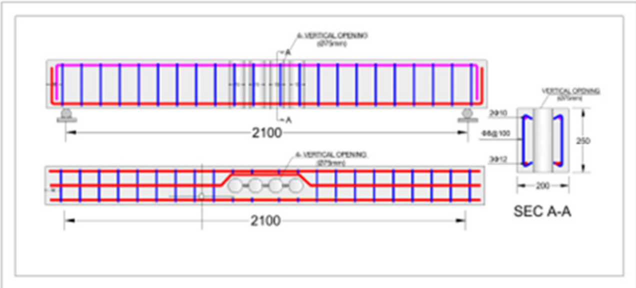
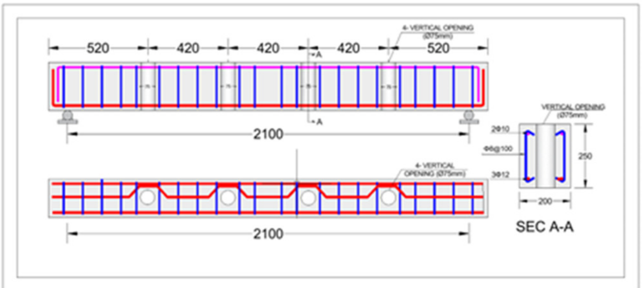


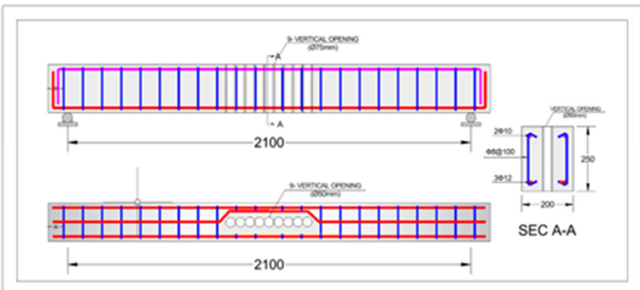
Fig. 2. Details of controlled RC beam.



(a)

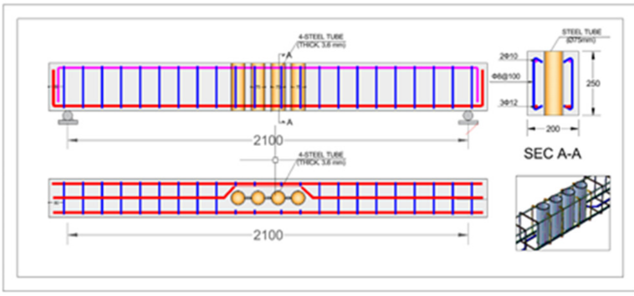


(b)

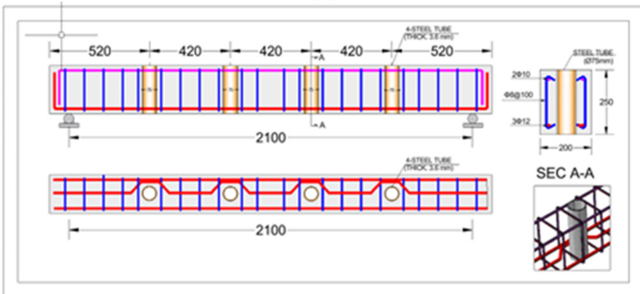


(c)

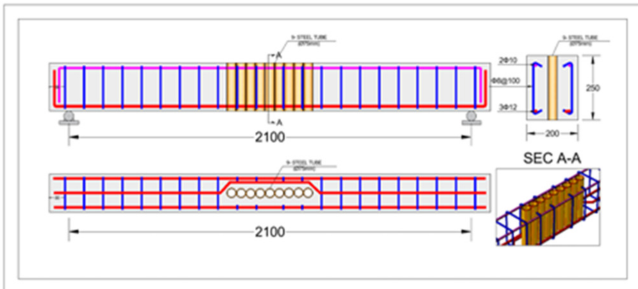
Fig. 3. Details for beams with openings: (a) B1-C-C4-WS, beam with an unreinforced 75 mm circular opening; (b) B2-N-C4-WS, beam with an unreinforced 75 mm circular opening; (c) B3-C-C9-WS, beam with an unreinforced 50 mm circular opening.



(a)



(b)



(c)

Fig. 4. Details for beams with strengthened openings:(a) B1-C-C4-ST, beam with a 75 mm circular opening reinforced with tubes; (b) B2-C-C4-ST, beam with a 75 mm circular opening reinforced with tubes; (c) B3-C-C9-ST, beam with a 50 mm circular opening reinforced with tubes.

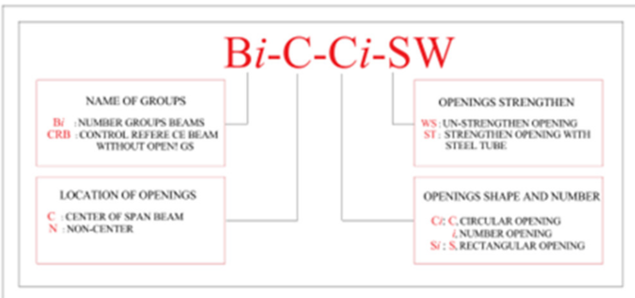


Fig. 5. The specimen's naming convention and its arrangement.

F. *Test Setup*

Seven specimens of concrete beams were tested for static loading using a hydraulic jack with a 500 kN capacity, whereas an applied load was controlled using a 1000 kN load cell. The applied load was increased gradually at an increment of 5 kN up to the failure. All beam specimens were supported as simple span and subjected to two equal external concentrated static loads, as shown in Figure 6. An LVDT device was used to measure the displacement at specific locations for each applied load increment for the control beams tested under static loading. It was placed at the mid-span of the bottom of the specimens. It provides accurate displacement measurements, recorded by a data logger, as portrayed in Figure 6. The cracks were marked, at the first crack, with a thick pen, and the load and midspan deflection were recorded.

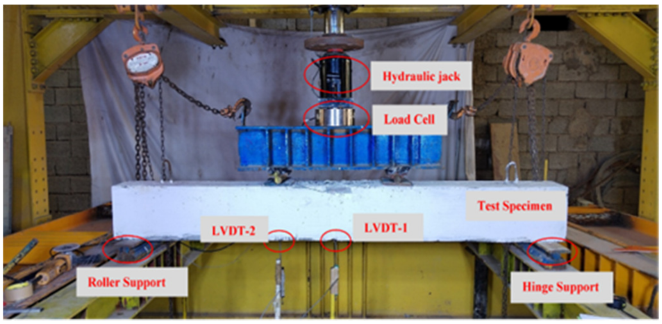


Fig. 6. Testing of specimens under two-point loading.

III. RESULTS AND DISCUSSION

The primary objective of this study is to investigate the strength and behavior of reinforced concrete beams with circular vertical openings. This study also examined techniques to recover the strength reduction in RC beams, which is caused by vertical openings, by strengthening them with steel plates.

A. *Ultimate Loads*

Table II shows that the load capacity of the beams with openings is reduced compared to the beams without openings. The load capacity of the beam B1-C-C4-WS is 27.7% lower than the referenced beam's ultimate load (CRB). Although the beams B2-N-C4-WS and B3-C-C9-WS show an ultimate load reduction of 28.5% and 27.7%, respectively, the reductions are similar because each specimen had the same opening area. In contrast, for the beam with a mid span opening [2], the strength reduction was 8.8%. This reduction can be attributed to the weakening of the cross-sectional area caused the width of the openings, which lowers the stiffness and resistance of the beam to the applied loads. Furthermore, the presence of the openings can cause stress concentrations around the opening edges. This distortion of stresses can lead to localized areas of higher stress, potentially affecting the overall durability of the beam. There is also, though to a lesser degree, a reduction in the load capacity due to the presence of openings in specimens that have steel tubes surrounding them. The load capacity reduction for the beams with openings B1-C-C4-ST, B2-N-C4-ST, and B3-C-C9-ST are 24.1%, 25.9%, and 23.9%, respectively, compared to the ultimate load of the reference beam. As a result, even a small increase in the ultimate load capacity is achieved by having a steel tube inside the openings, as opposed to openings without such a tube, with the improvement percentages ranging from 3.7% to 5.2%. The presence of a steel tube helps distribute the applied loads more efficiently throughout the beam, which reduces the localized stress concentrations. This can result in an improved load carrying capacity and overall structural integrity.

TABLE II. ULTIMATE LOAD CAPACITY

Group	Specimens	Ultimate load (kN)	Decreasing in ultimate load (%)	Improvement in ultimate load strength (%)
	CRB	112.3	Ref.	-
1	B1-C-C4-WS	81.10	27.7	Ref.
	B1-C-C4-ST	85.20	24.1	5.0
2	B2-N-C4-WS	80.20	28.5	Ref.
	B2-N-C4-ST	83.20	25.9	3.7
3	B3-C-C9-WS	81.20	27.7	Ref.
	B3-C-C9-ST	85.40	23.9	5.2

B. *Load-Deflection Curves*

Throughout the test, the applied load and mid-span deflection of each beam were measured at each load step and presented as load versus mid-span deflection curves. During the loading procedure, the specimens went through three behavioral stages. The load-mid-span deflection response exhibits linear behavior in the first stage. In contrast, the second stage involves the initiation of internal flexure cracks at the bottom face, around the openings, and in the strut connecting between the loading plate and the internal support. Finally, in the third stage, the rate of the rise in deflection is significantly greater than the rate of the increase in the applied load, until failure occurs as the load gets closer to its final value.

Two loading stages were selected to study the behavior of the beams with vertical openings under service load conditions. Deflection was recorded at the ultimate load and at 65% of the ultimate load for the reference beam (beam without opening).

In contrast to [2], where a 21% increase in the mid-span deflection is reported, Table III shows that, whether the opening was positioned at mid-span or distributed along the beam, the vertical openings increased the deflection at the same applied load level (70 kN) for unstrengthened specimens. That is, by approximately 18.5%, 37.48%, and 23.13% for specimens B1-C-C4-WS, B2-N-C4-WS, and B3-C-C9-WS, respectively, compared to the specimen CRB. This increase in deflection was due to a decrease in the moment of inertia.

The use of a steel tube around the opening had a positive effect on the deflection at the same applied load level in the midspan compared with the same specimen without strengthening. In group I, the specimen B1-C-C4-ST showed a 7.67% decrease in deflection compared to the specimen B1-C-C4-WS (without strengthening) in the same group. In Group II, a 9.4% decrease in deflection was observed for the specimen B2-N-C4-ST compared to B2-N-C4-WS. Finally, as shown in Figures 7–10, the deflection of the specimen B3-C-C9-ST in Group III was reduced by 15.93%.

TABLE III. DEFLECTION AT MIDSPAN FOR BEAMS

Group	Specimens	At 70 kN load (service load for solid beam)			At Ultimate load	
		Deflection (mm)	Increase in Deflection (%)	Improvement in deflection strength, (%)	Deflection (mm)	Variation of deflection (%)
	CRB	6.27	Ref.	-	12.32	Ref.
I	B1-C-C4-WS	7.43	18.50	Ref.	10.12	17.86
	B1-C-C4-ST	6.86	9.410	7.67	11.09	9.980
II	B2-N-C4-WS	8.62	37.48	Ref.	10.70	13.15
	B2-N-C4-ST	7.81	24.56	9.40	11.21	9.010
III	B3-C-C9-WS	7.72	23.13	Ref.	10.33	16.15
	B3-C-C9-ST	6.49	3.510	15.93	10.42	15.42

As demonstrated by the experimental results, strengthening the vertical openings with steel tubes leads to a reduction in the mid-span deflection, indicating that the additional reinforcement reduces the risk of localized failure by compensating for the loss in the beam's compression zone. By acting as an external confinement for the opening and halting the formation and spread of fractures, the steel tube can improve the flexural behavior of the beam. This confinement lowers the possibility of an early failure by preserving the beams' structural integrity.

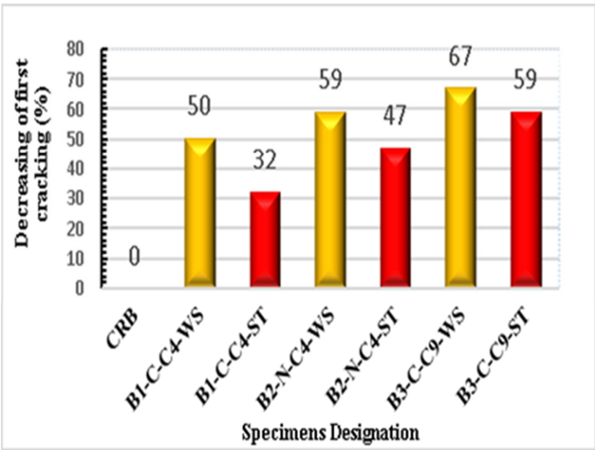


Fig. 7. Reduction in the first flexural cracking load.

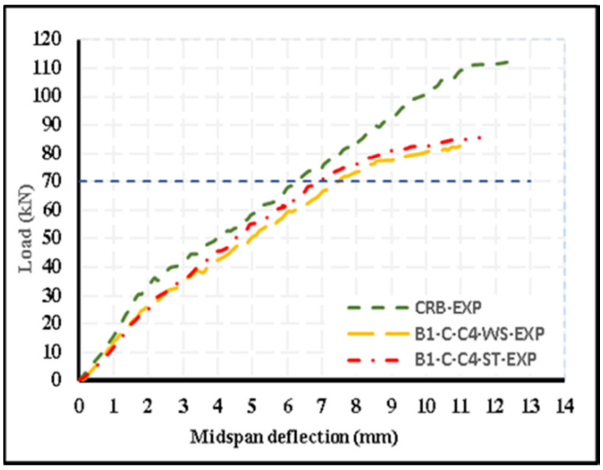


Fig. 8. Load-mid-span deflection curves of Group I beams.

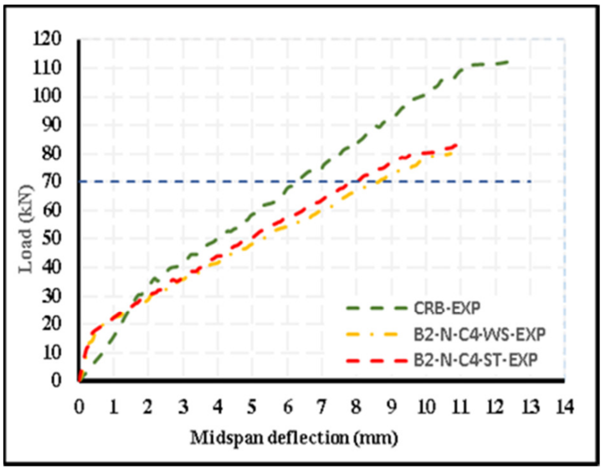


Fig. 9. Load-mid-span deflection curves of Group II beams.

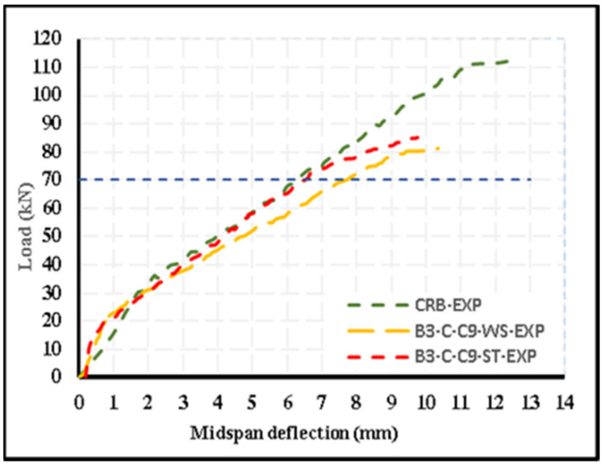


Fig. 10. Load-mid-span deflection curves of Group III beams.

C. Initial Cracks and Modes of Failure

The cracks in the solid beam initially developed near the tension zone before moving vertically in the direction of the neutral axis. Prior to collapse, the crack widths increased, and then there were 45-degree diagonal cracks, which caused an abrupt flexural failure. Figure 11 demonstrates how the flexural cracks developed in the bottom face at the middle zone of the beam at a load of 34 kN. In order to compare its behavior with that of other beams with openings, this beam was evaluated as a control beam. When compared to solid beams, the beams with openings exhibited a distinct behavior with the initial crack appearing at the opening's edges and spreading to other opening edges. The fracture patterns of B1-C-C4-WS, B2-N-C4-WS, and B3-C-C9-WS are displayed in Figure 12 and Table IV. It was observed that the initial cracking load decreased by 50%, 59%, and 67%, respectively, compared to the reference beam (CRB). The strength and resistance to cracking of the reinforced concrete beams had significantly declined and the fractures had spread to the load point at the upper chord of these openings. As the load increased, the flexural cracks were seen in several locations throughout the beam.

TABLE IV. FIRST CRACKING LOAD FOR BEAMS

Group	Specimens	First cracking load (kN)	Decreasing in first cracking load (%)	Improvement in first crack strength (%)
	CRB	34	0.0	0.0
I	B1-C-C4-WS	17	50%	Ref
	B1-C-C4-ST	23	32%	35%
II	B2-N-C4-WS	14	59%	Ref
	B2-N-C4-ST	18	47%	29%
III	B3-C-C9-WS	11	67%	Ref
	B3-C-C9-ST	14	59%	27%

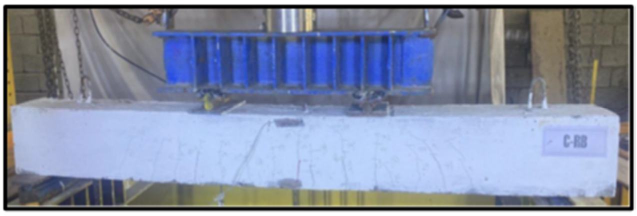
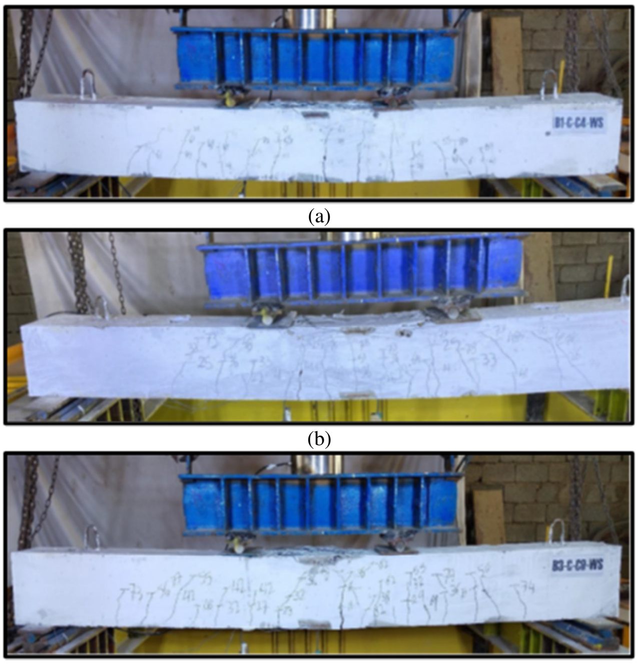


Fig. 11. Crack pattern for specimens CRB (solid).

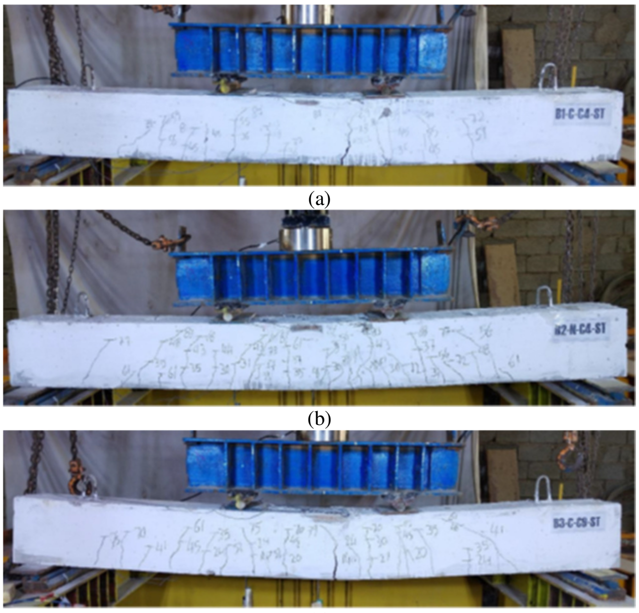


(a)

(b)

(c)

Fig. 12. Crack pattern for specimens without strengthening: (a) B1-C-C4-WS specimen, (b) B2-N-C4-WS specimen, (c) B3-C-C9-WS specimen.



(a)

(b)

(c)

Fig. 13. Crack pattern for specimens strengthened by steel tubes: (a) B1-C-C4-ST specimen, (b) B2-N-C4-ST specimen, (c) B2-C-C9-ST specimen.

The specimens B1-C-C4-ST, B2-N-C4-ST, and B3-C-C9-ST were found to have delayed initial cracks when reinforced with steel tubs around the vertical openings. Compared to the reference beam, B1-C-C4-WS, the corresponding decrease in the first cracking load values was 32%, 47%, and 59%, respectively. The presence of steel tubs obstructs the path of crack propagation, which required a higher energy to divert the cracks into flexural cracks along the mid-span. As the applied load increased, new diagonal cracks developed, approximately parallel to the original ones and located at the opposite corner of the opening. These cracks were accompanied by the simultaneous widening and extension of the existing cracks, as illustrated Figure 13 and Table IV.

IV. CONCLUSIONS

This study examined the impact of vertical openings on the structural performance of reinforced concrete beams and explored the effectiveness of steel tube reinforcement in reducing the strength losses. The key conclusions drawn from the experimental investigation are:

The presence of openings in the RC beams led to a reduction in the initial flexural cracking load. The percentages of reduction in the initial cracking loads for the beams with nine adjacent openings, and four adjacent and non-adjacent vertical openings, were 50%, 59%, and 67%, respectively, compared to the corresponding reference beam (i.e., the beam without openings). Additionally, using steel tubes around the vertical openings delayed the onset of early cracks by about 27-35% compared to the specimens in the same group without reinforcing tubes. Additionally, the creation of openings in the RC beams tends to decrease the ultimate strength and increase the mid-span deflection compared to the control beam. For the beams with four adjacent and non-adjacent vertical openings and nine adjacent openings, the percentage decrease in the ultimate load was 27.7%, 28.5%, and 27.7%, respectively, and the percentages increase in the mid-span deflection (at service load) was 18.5%, 37.48% and 23.13%, respectively, compared to the control beam.

Compared to the beams without any strengthening in the same group, the mid-span deflection at the 70 kN loading step decreased by 7.67%, 9.4%, and 15.93%, while the ultimate loads increased by 5%, 3.7%, and 5.2% when the vertical openings were made using a steel tube. The results demonstrated that the beams with multiple small openings, reinforced with steel plates and an equivalent total opening area, exhibited a better performance than those with larger individual openings.

REFERENCES

[1] H. H. Ali and A. M. I. Said, "Flexural behavior of concrete beams with horizontal and vertical openings reinforced by glass-fiber-reinforced polymer (GFRP) bars," *Journal of the Mechanical Behavior of Materials*, vol. 31, no. 1, pp. 407–415, Jul. 2022, https://doi.org/10.1515/jmbm-2022-0045.

[2] A. Y. Khadhair and A. F. Izzet, "Behavior of Reinforced Concrete Beams with Vertically Penetrated Holes across the Cross - Sectional Depth," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14301–14307, Jun. 2024, https://doi.org/10.48084/etasr.7192.

[3] H. H. Ali and A. I. Said, "Experimental Study on the Performance of Concrete Beams Including Holes Reinforced with Glass Fiber Polymer," *E3S Web of Conferences*, vol. 427, 2023, Art. no. 02010, https://doi.org/10.1051/e3sconf/202342702010.

[4] *Guide to Simplified Design for Reinforced Concrete Buildings*, ACI 314R-16, American Concrete Institute, Farmington Hills, MI, 2016.

[5] A. M. Morsy and A. M. Barima, "Behavior of R.C. Beams with Openings using Different Strengthening Techniques," *International Journal of Sciences: Basic and Applied Research*, vol. 46, no. 1, pp. 195–219, 2019.

[6] L. M. Olanitori and T. O. Tifase, "Effect of small transverse service holes on shear strength of reinforced concrete slender beams," *Journal of Applied Sciences and Environmental Management*, vol. 23, no. 3, Apr. 2019, Art. no. 539, https://doi.org/10.4314/jasem.v23i3.25.

[7] S. C. Chin and S. I. Doh, "Behaviour of Reinforced Concrete Deep Beams with Openings in the Shear Zones," *Journal of Engineering and Technology*, vol. 6, no. 1, pp. 60–71, Jun. 2015.

[8] J. H. Ling, J. T. S. Ngu, Y. T. Lim, W. K. Leong, and H. T. Sia, "Experimental Study of RC Hollow Beams with Embedded PVC Pipes," *Journal of Advanced Civil and Environmental Engineering*, vol. 5, no. 1, Apr. 2022, Art. no. 11, https://doi.org/10.30659/jacee.5.1.11-23.

[9] A. H. Aziz and A. E. Ajeel, "Effect of Existing Flange Openings and Cold Joints in Strength of RC T-Beams," *Journal of Engineering*, vol. 16, no. 01, pp. 4535–4546, Apr. 2010, https://doi.org/10.31026/j.eng.2010.01.11.

[10] R. J. C. Silva, M. B. S. Muniz, É. M. F. Lima, F. E. S. D. Silva Júnior, and C. V. D. S. Araújo, "Experimental analysis of reinforced concrete beams strengthened with steel bars and epoxy structural adhesive," *Revista ALCONPAT*, vol. 9, no. 1, pp. 65–78, Dec. 2018, https://doi.org/10.21041/ra.v9i1.213.

[11] A. S. Hamzah and A. Y. Ali, "Shear behavior of reinforced concrete beams with vertical and transverse openings," *Test Engineering and Management*.

[12] *Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete*, ASTM-A615/A615M-20, ASTM International, West Conshohocken, Pennsylvania, 2020.

[13] *Standard Specification for Concrete Aggregates*, ASTM-C33-C33M-18, ASTM International, West Conshohocken, Pennsylvania, 2018.