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Flexural Behavior of Reinforced Concrete Beams with Steel-Plate Reinforced Vertical Opening

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Abstract

The structural response of simply supported Reinforced Concrete (RC) beams with square vertical openings is investigated in this work. Studies were conducted using seven specimens of RC beams, with the aim of comparing beams with vertical openings to those without. Meanwhile, the other beams featured carefully positioned square openings. Note that one of these beams served as the control and had no openings. Each beam was the same length (1400 mm) with a 180×120 mm cross-section. Two-point loads were applied over a span of 1200 mm throughout the testing method, with a central load placed 300 mm from the ends. The openings were positioned in the middle of the span and came in three different widths: 20, 40, and 60 mm. Openings were made using either 1.5 mm thick square steel tubing or none at all. The major goal of this study was to determine whether the steel tube could compensate for the decrease in beam strength and the impact of decreasing beam cross-section (producing opening). Correspondingly, the beam ultimate load was found to decrease by 15.75%, 24.2%, and 32.5% for opening widths of 20 mm, 40 mm, and 60 mm, respectively, as the opening width increased. On the other hand, the performance gain for beams strengthened with steel plates when steel tubes were used was 11.78%, 12.14%, and 13.28% for the respective opening widths.

Keywords: Beam with an Opening; Flexural; Square Vertical Opening; Steel Tube.

1. Introduction

RC beams with openings are commonly used to construct new structures to improve accessibility and allow for the installation of necessary amenities like air-conditioning, water, and power supply [1]. Essentially, offering these services usually entails installing pipes and tubes beneath the ceiling, which may necessitate using suspended ceilings for aesthetic purposes. Nevertheless, this method leads to additional unutilized areas on every level. A practical and cost-effective solution can be achieved by including openings in the beams to eliminate the requirement for vast suspended ceilings. This approach particularly benefits tall buildings, resulting in significant cost savings [2]. On the other hand, numerous ducts and pipes that go through vertical openings in beams are hidden inside partitions until they reach their intended destination, as illustrated in Figure 1. This is a key factor contributing to the widespread use of vertical openings in Reinforced Concrete (RC) beams in contrast to horizontal openings, which can be deliberately placed without affecting the beam's compression zone or ultimate moment capacity [3]. Vertical holes naturally cause structural damage and lead to a reduction in the amount of concrete needed to produce the compressive stress block properly. The decrease in concrete area must be considered during the design process since it decreases the beam's ultimate strength in both flexure and shear. Moreover, the existence of vertical openings poses a potential hazard of severing or impeding the flexural and shear reinforcing bars. Consequently, it is essential to evaluate the influence of vertical openings on the performance and structural integrity of RC beams. This necessitates careful consideration and authorization from a certified design expert when designing such beams [4].

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Figure 1. Vertical services pipes (school building/Iraq)

In recent decades, several experimental studies have been carried out to investigate the effects of transverse openings on beams, specifically analyzing their shape and size [2, 5–9]. The placement of the holes has also garnered much scrutiny [10–12]. An important disadvantage of these openings is that they decrease the stiffness of the beam, resulting in more deflection and disturbing the natural distribution of load. This, in turn, leads to stress concentration and the formation of cracks at an earlier stage. Various proposals have been put up to tackle these difficulties. These methods consist of incorporating extra reinforcing steel [13–15] and employing Glass Fiber Reinforced Polymer (GFRP) for strengthening purposes [16, 17]. This has proven effective in reducing mid-span deflection, improving resistance against brittle failure, and utilizing different types of Fiber Reinforced Polymer (FRP) [18]. Moreover, incorporating steel plates in the reinforcement procedure has demonstrated encouraging outcomes in substantially enhancing strength and decreasing average deflection [19-21].

Although there has been much research on the subject, there is a lack of experimental investigations in the literature that specifically investigate the flexural behavior of reinforced beams with vertical holes [22-26]. Silva et al. (2016) [22] examined RC beams containing vertical openings. Conducting tests on five beams with dimensions of 150×100 mm, it was discovered that the beams encountered shear failure at the mid-span due to the presence of openings. However, the beams near the support underwent flexural failure without impacting the ultimate load. Beams that had openings located 60 mm away from the support exhibited a 19% decrease in the maximum load capacity due to shear failure. The utilization of ABAQUS software for finite element analysis revealed elevated principal tensile stresses in the area where the beam experienced failure. On the other hand, Paul & Auta (2021) [23] conducted an analysis of the effects of strengthening vertical circular openings in RC beams (200×230×700 mm) using different materials. Enhancing the openings increased load capacity and strength. Using a 4 mm gauge steel plate increased the ultimate load by 15-17% and the flexural strength to 15 N/mm^2 compared to openings that were not reinforced. Galvanized steel tubing with a thickness of 2 mm and STM also enhanced the load capacity and strength by 9-11% and 3-5%, respectively.

Alshimmeri & Al-Maliki (2023) [14] conducted a study on six beams, each measuring 1000 mm in length, 180 mm in height, and 120 mm in breadth. The beams are supported at their extremities. Four of these beams have elongated openings of different dimensions, either measuring 40×40 mm or 80×40 mm. The study investigates the influence of vertical steel reinforcement, opening size, and orientation on the structural response of these beams to applied loads. Note that experimental testing quantifies the load deflection at the tension zones' central and quarter locations. The findings indicate that the existence of empty cavities decreases the load-bearing capability by around 37.14% to 58.33% in comparison to solid beams possessing identical attributes. Additionally, it results in a rise in deflection, varying from 71.6% to 75.5% for hollow ratios ranging from 7.4% to 14.8%. By increasing the quantity of shear steel reinforcement, deformations at all loading stages are reduced, particularly after the initial cracking. This also improves the ultimate load capacity of the beams by roughly 31.5% when the shear steel reinforcement is raised by around 50%.

A study was conducted by Mohammed et al. (2023) [25] on 11 RC deep beams. The beams underwent failure testing, with a specific focus on crucial elements such as the position, shape, and strengthening technique of the vertical opening. The presence of openings impacts the ultimate load (Pu) and, to a certain degree, the stiffness of the beams. Shear span openings resulted in a fall of 12-19% in Pu, while openings in the constant-moment area generated an 8-13% reduction. The opening configuration also influenced the outcome, with rectangular openings resulting in the most significant decrease, circular openings resulting in the least significant decrease, and square openings falling in between. To mitigate these impacts, two strategies were proposed: employing Ultrahigh-Performance Concrete (UHPC) in the vicinity of the opening and fortifying the surrounding region with both horizontal and vertical steel bars. Both approaches demonstrated efficacy, leading to a 14% and 10% augmentation in Pu when compared to beams lacking reinforcement and featuring openings in the shear and moment areas, respectively. The study also contrasted the experimentally derived Pu values with those computed using the Strut-and-Tie Model (STM) and a formula based on current US standards. The STM model underwent modifications to enhance its predictive capabilities, leading to an analytical-to-experimental Pu ratio ranging from 0.99 to 1.05.

Ali & Said (2023) [24] investigated the effects of inserting holes in concrete beams reinforced with GFRP bars. The inclusion of vertical openings resulted in a 27.8% decrease in the maximum load capacity of the beams and a 39% increase in mid-span displacement, as compared to beams that did not have any openings. Hence, utilizing two nearby openings instead of a single one results in a reduction in beam strength. This highlights the significance of considering the design of RC beams and the possible utilization of GFRP bars as reinforcement. The presence of openings affects the strength of the beams, leading to decreased performance and greater displacement across medium spans.

According to prior analysis, vertical openings facilitate access to important services. However, few studies have evaluated the flexural characteristics of these beams. This study aims to empirically examine the flexural performance of beams reinforced with steel tube plates to address these knowledge gaps, focusing on the efficacy of using 1.5 mm thick steel plates. The impact of vertical square openings on the structural performance of simply supported RC beams will be examined. The influence of pre-existing vertical openings on RC beams will be assessed. Several criteria, such as the presence and width of openings and the effectiveness of using 1.5 mm thick steel plates, will be investigated to identify strategies for restoring beam strength.

2. The Experimental Work

This experimental study aims to evaluate the performance of simply supported RC beams concerning vertical square openings and the effectiveness of the insertion of steel tubes in assigning the properties of the artificially generated concrete opening. The research involves conducting tests on RC beams that have been reduced in size by a scaling down factor of one-three: they have a cross-sectional area of 180×120 mm, a total length of 1400 mm, a span of 1200 mm, and a central two-point load spaced at 300 mm. The investigation looks at the beams' flexural behavior and evaluates how previous vertical openings affected the way the beams functioned. This study used a mixture of ordinary Portland cement Type I from local manufacturers. The cement was manufactured following the recommendations of Iraqi Standard (IQS 5/2019) [27] and has the chemical composition and physical properties listed in Table 1. Local natural sand from Al-Kut City was used as the fine aggregate, while local natural gravel was adopted as the mixtures' coarse aggregate. The maximum particle sizes of the fine and coarse aggregates were 4.75 and 10 mm, respectively. Correspondingly, the sieve analysis and properties of the sand and gravel were tested per the Iraqi Standards (IQS 45/1984) [28]. The physical properties of the used sand and gravel are listed in Table 1, while their grading analyses are shown in Figure 2. Both aggregates were well-washed and surface-dried before being used to remove the dust and other pollutants from the particle surfaces.

Table 1. Chemical Composition and Physical Properties of Cement

Oxide	Content (%)	Property	Value
CaO	60.5	Loss of ignition (%)	1.95
SiO_2	21.2	Specific surface (m^2/kg)	377
Al_2O_3	4.52	Specific Gravity	3.12
Fe_2O_3	3.2	Initial setting time (min)	120
SO_3	2.03	Final setting time (min)	270
MgO	2.98	Compressive strength 2 days (MPa)	25.25
C_3A	6.45	Compressive strength 28 days (MPa)	48.8

Similar 1.5 mm thick steel rolled tubes, which were accessible locally and came in a variety of square cross-section sizes, were used to strengthen the holes. The sand coating was applied to these tubes to give them a rough look. Tensile testing was conducted in compliance with ASTM 370-24 [29], and Table 2 provides a brief overview of the steel tubes that were utilized.

Table 2. Square steel tube properties used in this study

Steel tubes	1	2	3
Outer sides length (mm)	20.0	39.9	60.0
Area of the hollow tube (mm^2)	400	1592	3600
Normal thickness (mm)	1.5	1.5	1.5
Measured thickness (mm)	1.5	1.51	1.5
Yield stress fy (MPa)	490.5	482.5	423.0
Ultimate strength fu (MPa)	667.76	636.1	508.96
Elongation, %	25	25	23

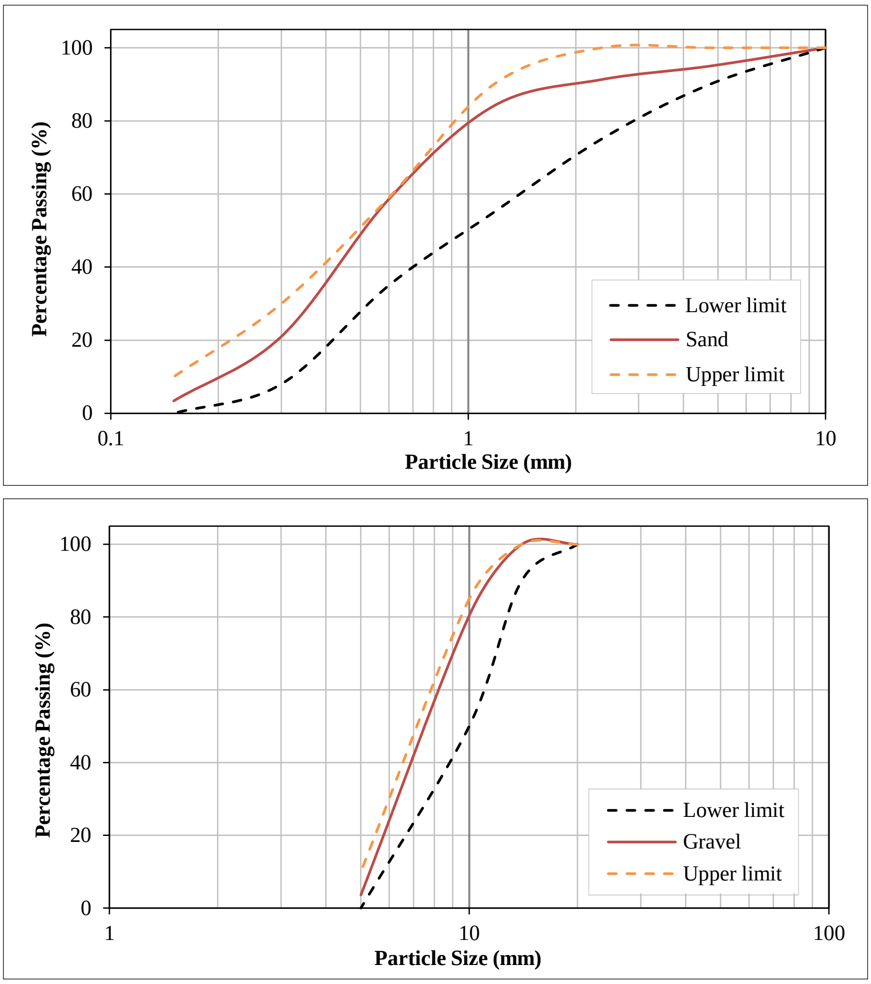


Figure 2. Sieve Analysis of Fine and Coarse Aggregates

The beams are designed with an adequate amount of longitudinal and shear reinforcement to cause flexural failure. The bottom reinforcement consisted of 2Ø12 mm deformed bars, while the top chord was reinforced with 2Ø6 mm bars. In addition, the shear span is strengthened with an appropriate quantity of 6 mm diameter steel stirrups to prevent failure due to shear forces. The stirrup placement consists of the initial stirrup positioned 40 mm before the support face, followed by a further eight stirrups placed at intervals of 75 mm, resulting in a total distance of 560 mm from the support face. Note that this configuration results in a central section with a width of 80 mm, which can accommodate vertical holes of 60 mm in diameter and be covered with concrete on the sides. Tensile testing was performed according to the ASTM A615/A615M-20 [30] and ASTM A496/A496M-07 [31] standards. Table 3 presents comprehensive characteristics of the steel reinforcement. Figure 3 displays the specific information about the reinforcement.

Table 3. Properties of steel reinforcement

Nominal bar diameter (mm)	Measured bar diameter (mm)	As (mm^2)	Yield stress (MPa)	Ultimate strength (MPa)	Elongation (%)
6	5.82	28.27	476.80	596.08	-
12	11.82	113.1	600.79	703.36	12.53

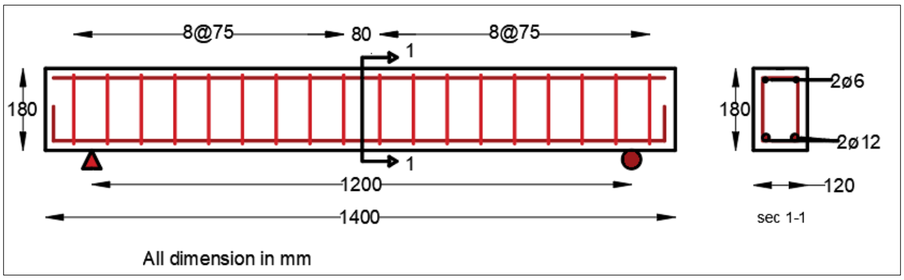


Figure 3. Geometric and reinforcement details (side view)

To easily identify the description of each beam, a distinct designation was allocated to all beams, indicating their characteristics, such as whether they were solid or had an opening. For the arrangement and clarification of the specimen naming convention, please refer to Figure 4. To obtain a thorough overview of the tested beams, including their descriptions and details, check Table 4.

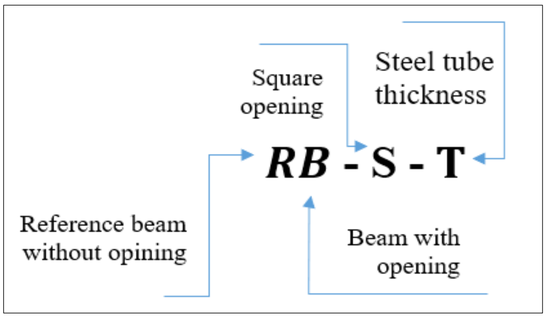


Figure 4. The arrangement and definition of specimen naming convention

Table 4. Description and details of the tested beams

No.	Specimen designation	Steel tube thickness (mm)	Openings width (mm)
1	R-solid	Nor	-
2	B-S20	Nor	20
3	B-S40	Nor	40
4	B-S60	Nor	60
5	B-S20-T1.5	1.5	20
6	B-S40-T1.5	1.5	40
7	B-S60-T1.5	1.5	60

Meanwhile, strengthened beams are simply constructed by placing steel tubes to form the opening integrally with the concrete, and openings were made using prefabricated styropor shapes and positioned into the beam before casting. To give the steel tube a rough surface, sand blasting was applied to it. The adhesion between the tubes and the concrete was enhanced by this surface treatment. Figure 5 illustrates detailed information on the steel tube, including details on surface roughness. A brief summary of the steel tubes used is provided in Table 5.

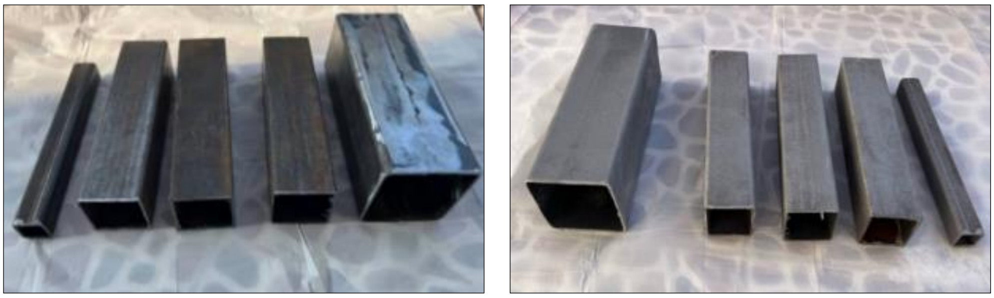


Figure 5. Steel tubes and details of tubes roughening

Table 5. Square steel tube properties used in this study

Steel Tubes	Outer Sides Length (mm)	Area of the hollow tube (mm^2)	Normal Thickness (mm)	Measured Thickness (mm)	Yield Stress fy (MPa)	Ultimate Strength fu MPa)	Elongation, (%)
1	20	400	1.5	1.5	490.5	667.76	25
2	40	1600	1	1	482.96	611	21
3	39.9	1592	1.5	1.51	477.5	636.1	25

Following a 28-day curing period, the beam specimens were subjected to a minimum of 24 hours of drying. To facilitate the discovery of cracks, the surfaces of the beams were painted white. The beams were placed in the testing frame, ensuring the centerline, supports, point load, and Linear Variable Differential Transformers (LVDT) were properly aligned. Note that hydraulic testing equipment with a maximum load capacity of 1000 kN was used to apply a continuously increasing load. The load was measured by a top load cell, as depicted in Figure 6. The load progressively increased in increments of 5 kN, measuring imposed load, midspan deflection, and strain.

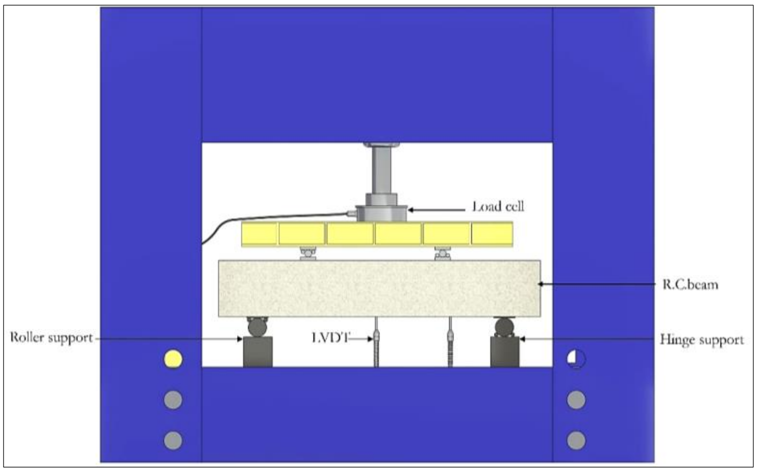


Figure 6. Test rig

Prior to conducting the tests, the beams underwent dimensional verification, visual examination, and comprehensive documentation of all relevant information. The Linear Variable Differential Transformers LVDTs were positioned, and the load was gradually increased until failure occurred. The LVDT was placed in the middle of the span. At the initial occurrence of cracks, they were identified and noted using a bold pen. Additionally, measurements of load, midspan deflection, and strain were taken. A total of seven specimens were analyzed (see Figures 7 to 9). Among these, one beam functions as an unobstructed reference, while the other beams display openings.

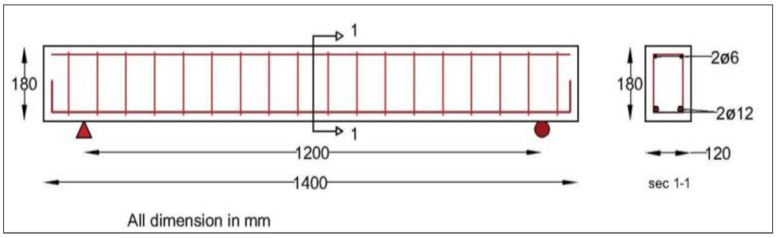
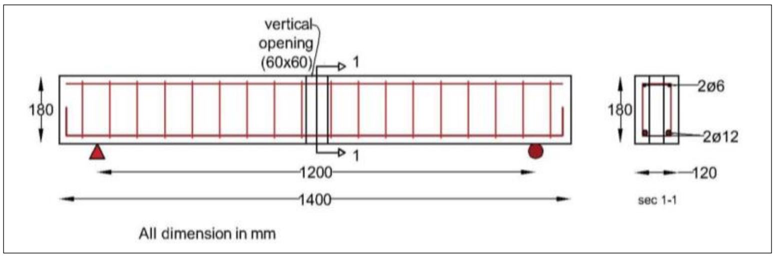
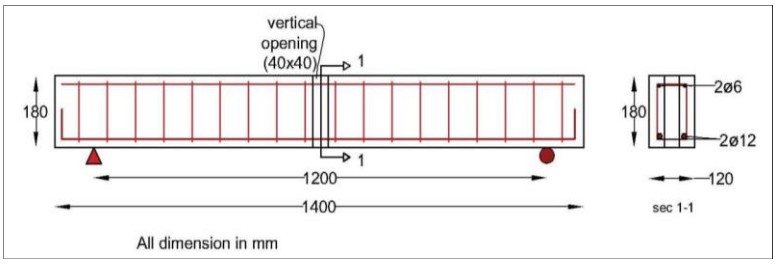


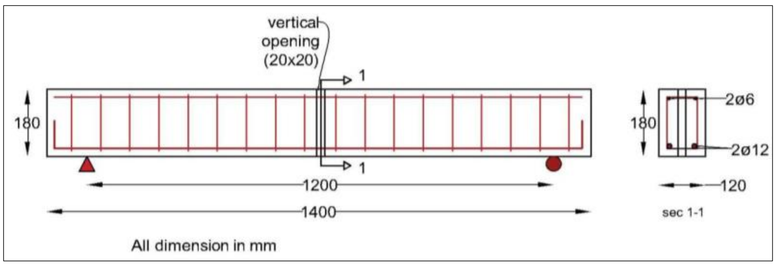
Figure 7. Geometric and reinforcement details for the reference beam



(a) B-S60, a beam with an unreinforced 60 mm square opening

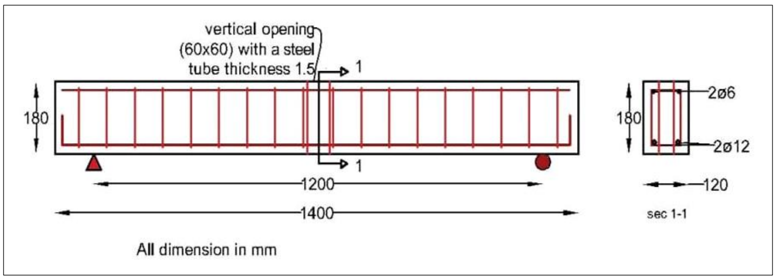


(b) B-S40, a beam with an unreinforced 40 mm square opening

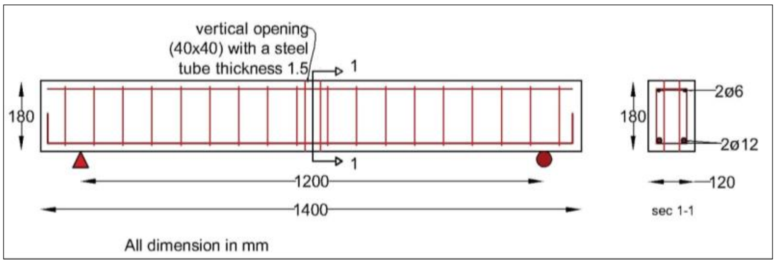


(c) B-S20, a beam with an unreinforced 20 mm square opening

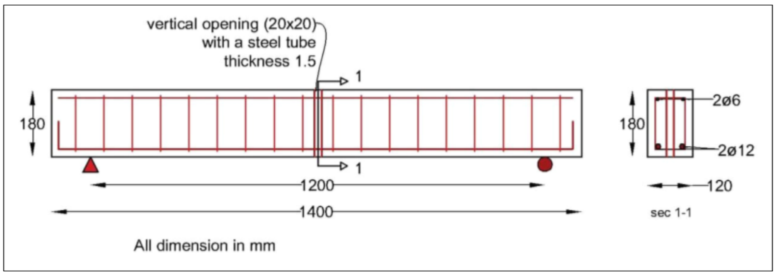
Figure 8. Geometric and reinforcement details for beams with openings



(a) B-S60-T1.5, a beam with a 60 mm square opening reinforced with plates



(b) B-S40-T1.5, A beam with a 40 mm square opening reinforced with plates



(c) B-S20-T1.5, a beam with a 20 mm square opening reinforced with plates

Figure 9. Geometric and reinforcement details for beams with strengthened openings

With widths varying from 60 to 40 to 20 mm, the beam holes are positioned thoughtfully in the middle of the span. Out of the six instances, three have beams with openings but no strengthening steel tube, whereas the remaining three have openings that house 1.5 mm thick steel tubes. The goal of this setup is to investigate the effects of strengthening steel tube reinforcement. The flow chart is described in the following part, which describes the processes of the whole work regarding the beams with different openings, see Figure 10.

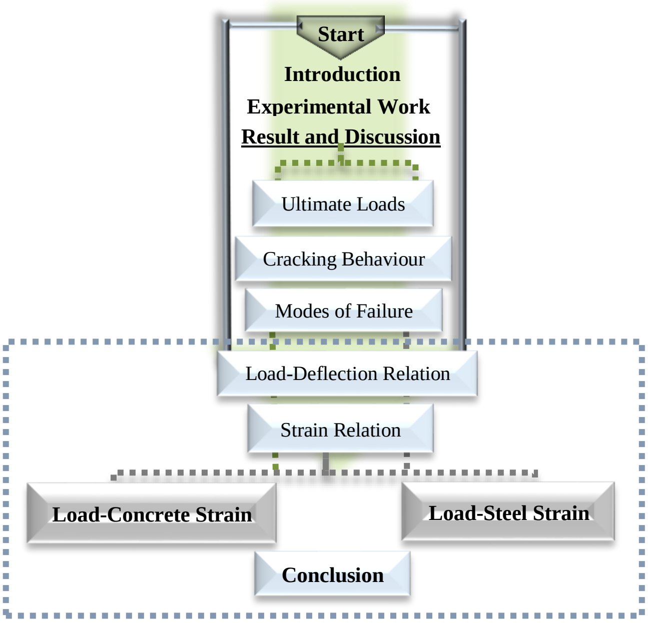


Figure 10. The flowchart explains the whole experimental design

3. Result and Discussion

This research aims to examine the impact of vertical square openings on the performance of simply supported RC beams. Therefore, the objective is to assess the influence of pre-existing vertical openings on the performance of RC beams and investigate several factors, such as the presence of openings, their breadth, and the effectiveness of using steel plates with a thickness of 1.5 mm, to identify methods for restoring beam strength.

3.1. Ultimate Loads

Table 6 displays the maximum load capacity (Pu) for beams susceptible to flexural failure. Typically, beams have reduced load capacity when there are openings, as illustrated in Figure 11. The load capacity of beams with openings (B-S20) is reduced by 15.75% compared to the reference beam. The decline in question is significantly smaller when compared to specimens B-S40 and B-S60, which demonstrate declines of 24.2% and 32.5%, respectively. This discovery is consistent with the findings reported by previous studies [7, 32]. The observed decrease can be attributable to the reduction in the required concrete area for the complete formation of compressive stress block at the ultimate load. Therefore, inserting a vertical square opening in the midsection of a RC beam reduces its ultimate load due to decreased effective cross-sectional area, interrupted reinforcement continuity, and increased stress concentration around the opening. Specifically, it diminishes the moment of inertia of the beam's cross-sectional area, decreasing its ability to resist bending and deformations under load.

Table 6. Ultimate load capacity and deflection at mid-span

Specimens	Ultimate load (kN)	Reduction in ultimate load (%) *	Percentage of improvement (%)**	Deflection at ultimate load, δu (mm)
R-Solid	120	-	-	12.88
B-S20	101	15.75	-	9.9
B-S40	90.9	24.2	-	7.5
B-S60	81	32.5	-	7.04
B-S20-T1.5	113	5.83	11.78	11.76
B-S40-T1.5	102	15	12.14	8.43
B-S60-T1.5	91	23.53	13.28	7.29

* Reduction in ultimate load with respect to R-Solid.

** Percentage of improvement with respect to elements without steel plates

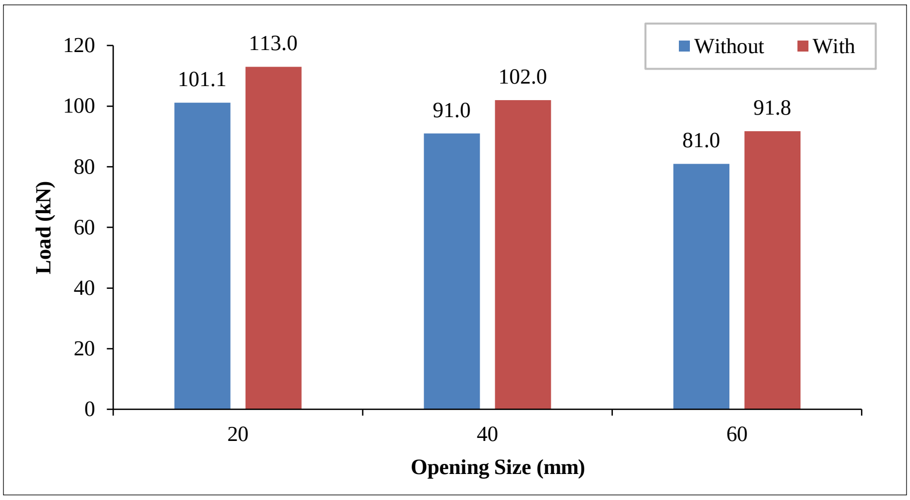


Figure 11. Load-opening width relationship chart

Concerning specimens containing steel tubes with a thickness of 1.5 mm, there is likewise an observed reduction in load capacity when an opening occurs. However, the decline is not as significant. The load capacity loss for beams with openings (B-S20-T1.5) is 5.83%, while for (B-S40-T1.5) and (B-S60-T1.5), it is 15% and 23.53%, respectively, when compared to the ultimate load of the reference beam. Figure 12 depicts this tendency. Therefore, the inclusion of a steel plate within the opening substantially enhances the maximum load capacity in comparison to those lacking a steel plate. The presence of reinforcement led to improvement percentages of 11.78%, 12.14%, and 13.28% for specimens with opening widths of 20, 40, and 60, respectively, as depicted in Figure 13. Similar findings were previously reported in previous studies [19, 23]. This finding demonstrates that the inclusion of steel plates greatly enhanced the structural integrity of RC beams. Note that this improvement can be attributed to the internal resistance of the specimen, particularly in the lower tension zone, which remained unaffected by the presence of the existing opening due to the lateral removal of the tensile reinforcement instead of being abruptly severed. Conversely, the top compression zone decreased and is insufficient for the current opening. Steel tubes reinforce the upper zone and enhance the compressive force in conjunction with the concrete.

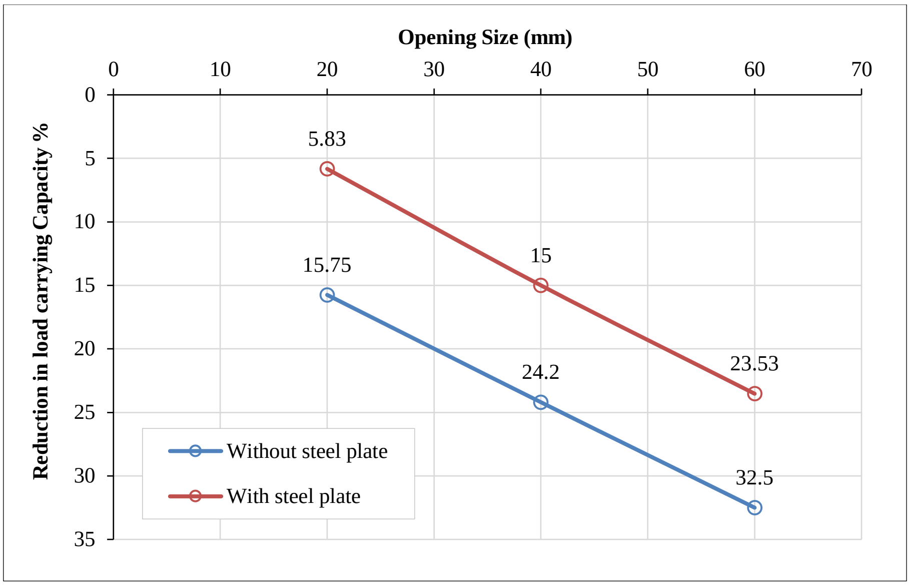


Figure 12. Effect of the opening width (with and without plate)

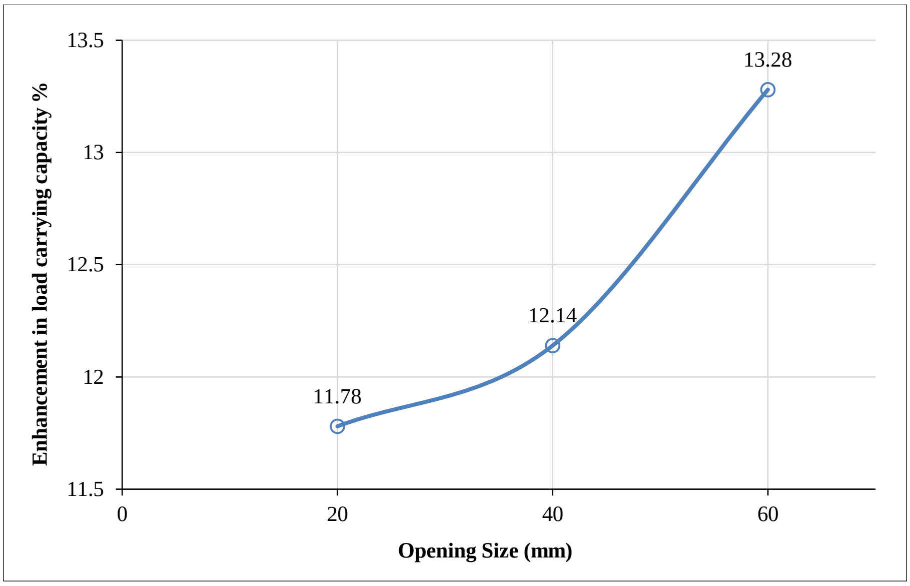


Figure 13. Percentage of improvement with the inclusion of steel plates

3.2. Cracking Behavior

During the initial loading, RC beams are in a state without cracks. When the applied load becomes stronger than the tensile strength of the concrete, cracks start to form from the part of the cross-section that is under tension. Usually, the initial crack appears as a vertical flexural crack in the area where pure bending occurs. The experimental results, outlined in Table 7, provide valuable information about the beginning of cracks. The beam labeled B-S20 undergoes a decrease of 10.89% in the load at which it first cracks when compared to the reference beam. On the other hand, specimen (B-S20-T1.5) shows a significant 5.45% reduction in the initial cracking load compared to the reference beam. This decrease is due to the inclusion of steel plates that reinforce the beam.

Table 7. Ultimate load experimental first cracking load

Specimens	First cracking load (kN)	Reduction in cracking load (%)
R-Solid	20.2	-
B-S20	18	10.89
B-S40	17.1	15.34
B-S60	16.1	20.29
B-S20-T1.5	19.1	5.45
B-S40-T1.5	17.5	13.36
B-S60-T1.5	16.6	17.82

The analysis includes the remaining samples that have comparable features but differ in cross-sectional dimensions. Cracks emerge intermittently during the crack formation process, initially appearing in a vertical orientation and concentrated in the center zone before spreading to the shear span. As the load increases, further cracks appear at an angle due to pressures that cause the material to slide, known as web-shear cracks. Moreover, vertical fractures that initially appear at the shear span gradually change their direction and become inclined towards concentrated loads due to the combined effects of flexural and shear forces. These cracks are referred to as flexural-shear cracks. Ultimately, as the loading persists, the existing fissures expand until no new cracks appear.

Figure 14 illustrates that only the R-Solid, B-S20-T1.5, and B-S40-T1.5 specimens exhibited diagonal cracks that extended toward the nearest concentrated load and penetrated the concrete compression zones at the loading site. This can be attributed to their higher load capacity. Conversely, the B-S60 specimen exhibits the fewest cracks due to its reduced load capability. Note that cracks tend to increase near the opening because of the elevated stress concentration.

(a) R-solid specimen

(b) B-S20 specimen

(c) B-S40 specimen

(d) B-S60 specimen

(e) B-S20-T1.5 specimen

(f) B-S40-T1.5 specimen

(g) B-S60-T1.5 specimen

Figure 14. Crack patterns at failure for (side view)

3.3. Modes of Failure

As previously stated, the RC beams were designed to break specifically due to flexural tension. During testing, a recurring kind of failure was repeatedly seen, characterized by the main reinforcement bars giving way and subsequently causing the concrete to be crushed. Regarding the reference beam, failure occurred close to the middle of the span. However, for beams with vertical openings, failure occurred at the section where the opening is located, as shown in Figure 15-a to 15-f. However, when steel plates were used to strengthen the beam. The presence of the steel tube further complicates the stress distribution, potentially causing localized areas of high stress. As the load increases, these high-stress areas exceed the material's tensile strength and steel concrete bond strength, resulting in the formation of cracks around the opening. It has been shown that a separation of the steel tube beneath the beam occurs with increasing load curvature, as exhibited in Figure 15-g to 15-j.

(a) B-S20 (bottom view)

(b) B-S20 (top view)

(c) B-S40 (bottom view)

(d) B-S40 (top view)

(e) B-S60 (bottom view)

(f) B-S60 (top view)

(g) B-S20-T1.5 (bottom view)

(h) B-S20-T1.5 (top view)

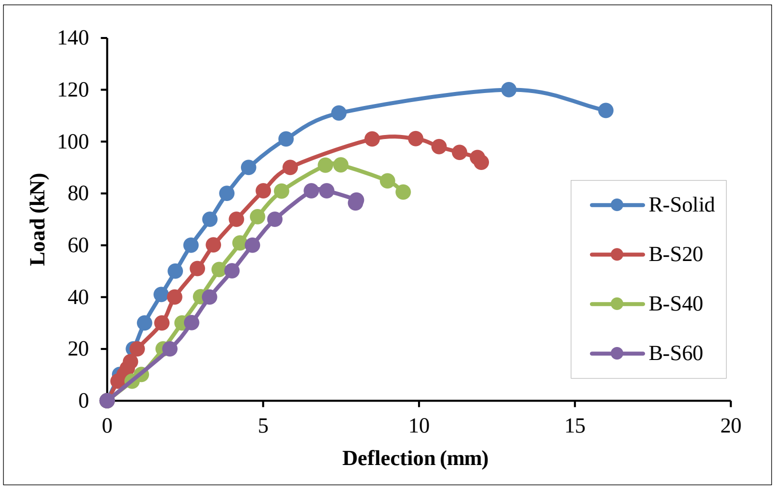
(i) B-S40-T1.5 (bottom view)

(j) B-S60-T1.5 (bottom view)

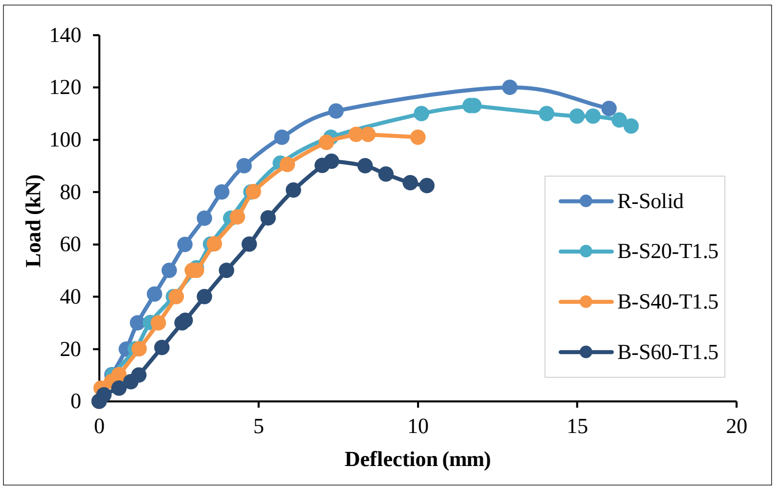
Figure 15. Specimens failing at vertical openings (bottom and top view).

3.4. Load-Deflection Relation

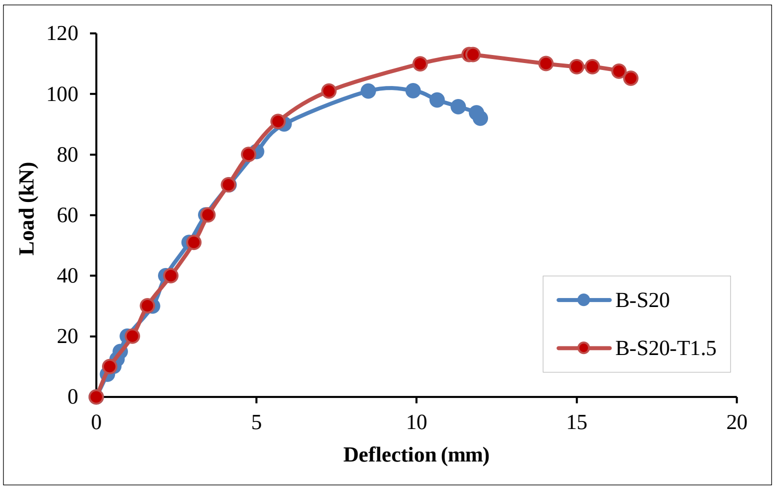
Figure 16-a portrays that the reference beam, labeled as R-Solid, exhibited better load-bearing and deflection properties than beams with openings due to its uninterrupted and continuous structure. The comparison of load-deflection curves for beams designated B-S20, B-S40, and B-S60 shows a continuous pattern of reduced load capacity and higher deflection rates after the initial cracking, which is worsened by the existence of openings. It was seen that the deflection values increase gradually as the holes spread under the same applied force, suggesting a direct relationship between the width of the opening and decreased stiffness. Moreover, as the applied load nears the maximum capacity, there is a significant rise in deflection for a specific load compared to the reference beam. This clearly demonstrates the negative effect of openings on structural performance.



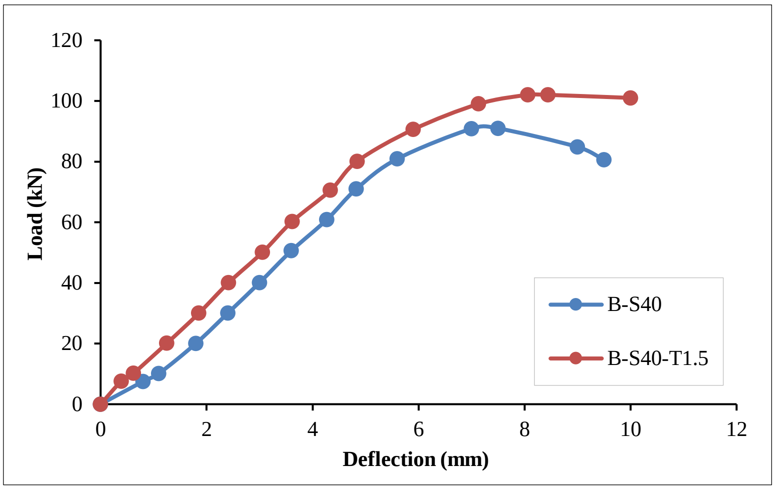
(a) The effect of openings without steel plates.



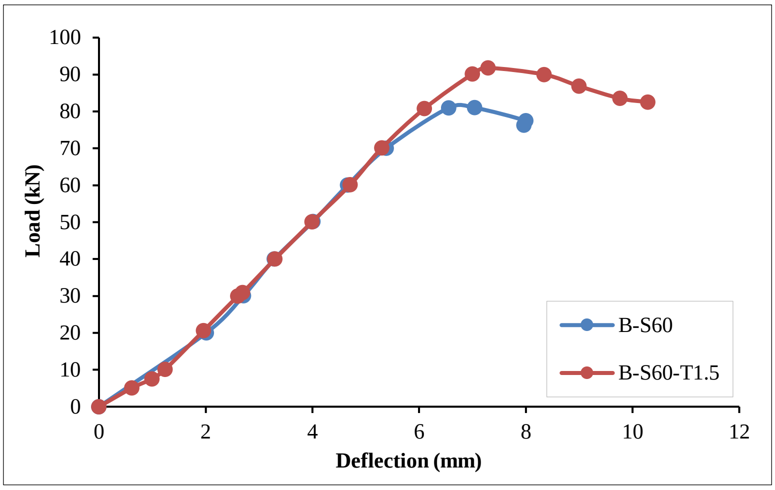
(b)The effect of openings with steel plates.



(c) The effect of the opening width is 20 mm (with and without plate).



(d) The effect of the opening width is 40 mm (with and without plate).



(e) The effect of the opening width is 60 mm (with and without plate).

Figure 1. Experimental load-midspan deflection curves

A similar behavioral trend can be noticed when analyzing Figure 16-b, although the measured values are considerably larger. The variance can be due to the incorporation of steel plates within the openings, which improve the beam's strength and stiffness, partially reducing the negative impacts caused by the openings. Figure 15-c to 15-e presents a comparison of load-deflection curves for beams with openings, both with and without plates that have the same opening widths. On the other hand, Figure 16-c clearly shows that at the beginning, the deflection curves for B-S20-T1.5 and B-S20 specimens are identical. However, as the load increases and approaches the ultimate load, they start to diverge, with the B-S20 specimen showing greater deflection at equivalent loads. The addition of plates to B-S20-T1.5 results in increased yield and ultimate load capabilities compared to B-S20 without plates.

Figure 16-d clearly illustrates the better flexural performance of B-S40-T1.5 compared to B-S40. Correspondingly, the trend seen in Figure 16-e also applies to specimens B-S60-T1.5 and B-S60, demonstrating a consistent pattern of improved performance in beams with plates.

3.5. Strain Relation

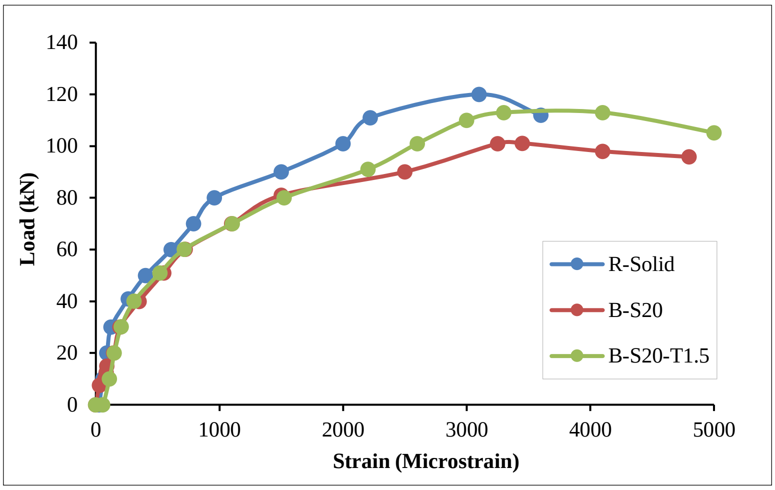
3.5.1. Load-Steel Strain Relationships

Figure 17 displays the load-steel strain curves of the tested specimens. Each specimen exhibited a recorded strain during the failure stage of the flexural steel reinforcement that surpassed the yield strain of the steel, which is 3000 Micro strain. This signifies substantial plastic deformation of the steel beyond its yield point prior to failure under the applied stress.

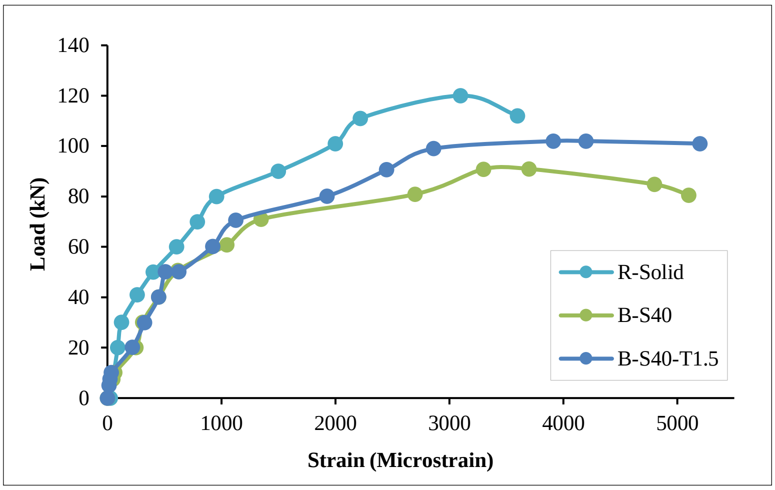
The ultimate steel strain values for specimens (B-S20) and (B-S20-T1.5) rose by roughly 25% and 28%, respectively, compared to the reference specimen (R-Solid). Similarly, a 29% rise was reported for specimens (B-S40), and a 30.76% increase was observed for specimens (B-S40-T1.5). Furthermore, specimens (B-S60) and (B-S60-T1.5) exhibited growth rates of around 30.77% and 31.43%, respectively, in comparison to the reference specimen.

Additionally, it was observed that the steel strain values of specimens reinforced with steel tubes were higher than those of specimens without steel tubes, and the latter were higher than the strain values of the reference beam. This demonstrates that the existence of gaps in beams diminishes their total load-bearing capability, focuses stress around the openings, alters structural behavior, and undermines flexural stiffness, all resulting in heightened strain.

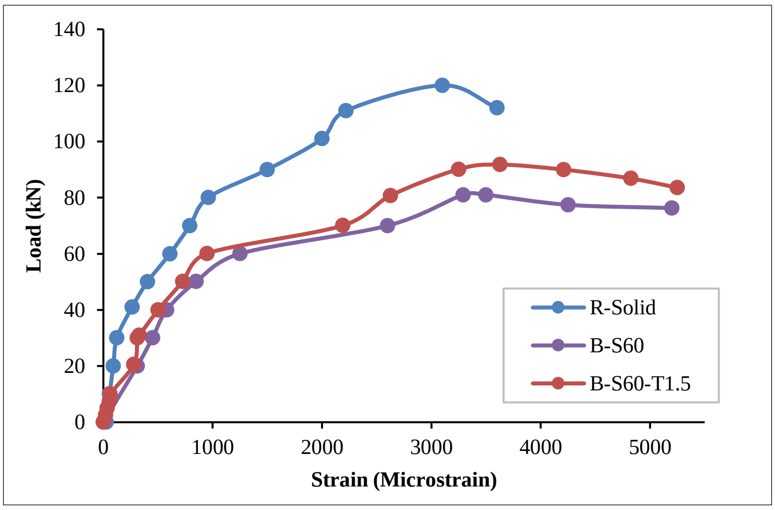
However, the utilization of steel tubes for reinforcement improves the structural performance of the specimens by augmenting their load-carrying capacity and allowing the redistribution of strain. This leads to an increased load-bearing capacity and overall performance in comparison to specimens lacking reinforcement.



(a) Load-steel strain curves of B-S20, BS20-T1.5.



(b) Load-steel strain curves of B-S40, BS40-T1.5.



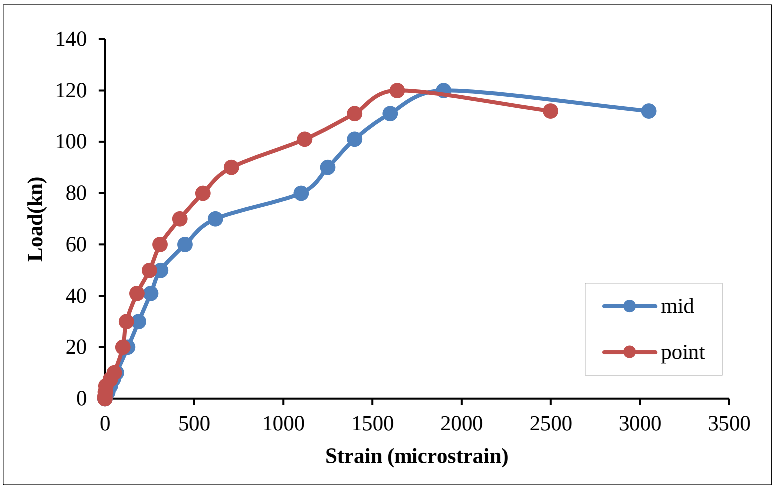
(c) Load-steel strain curves of B-S60, B-S60-T1.5.

Figure 2. Load-steel strain curves

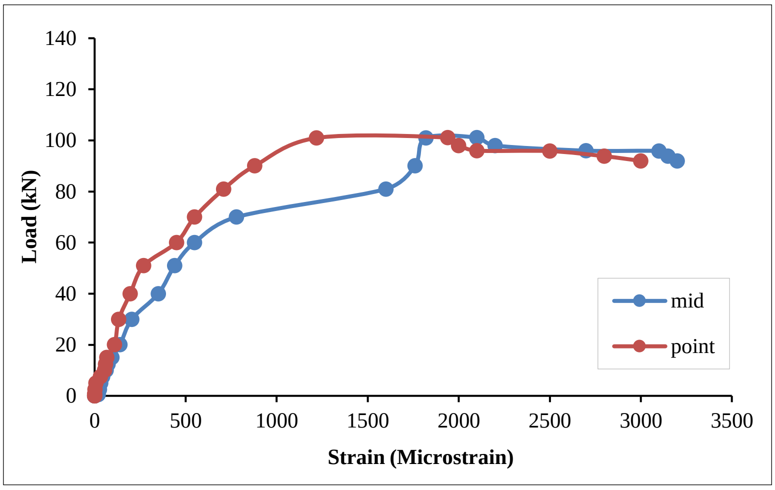
3.5.2. Load-Concrete Strain Relationships

The correlation between load and strain was evaluated utilizing the strain gauge. Two strain gauges were placed on the upper surface of the specimens: one at the midpoint next to the opening and the other positioned 60 mm apart center-to-center, as illustrated in Figure 18. The measurements indicate that the strain at the midpoint next to the opening consistently surpasses the strain observed away from the opening, with an increase ranging from 3% to 22%. In addition, the strain levels are greater in samples containing openings compared to the reference beam. The increases range from 5% to 12% for gauges near the opening and 10% to 20% for gauges located distant from the opening. Figure 19 illustrates this.

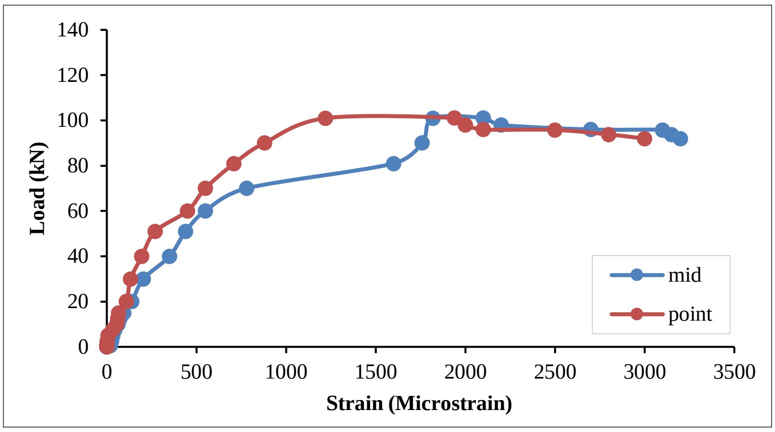
Figure 3. Connecting strain gauges to the concert (top view)



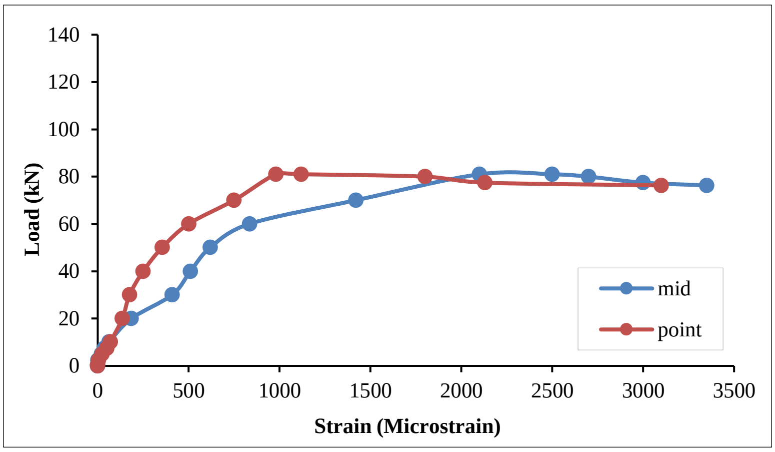
(a) Load-concrete strain curves of R-solid.



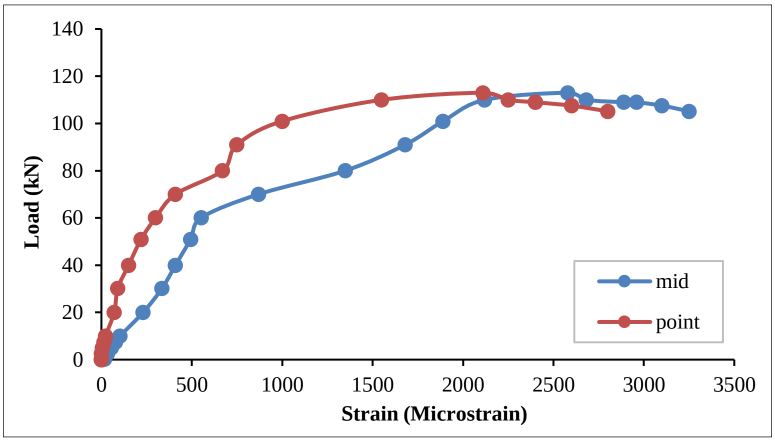
(b) Load-concrete strain curves of B-S20.



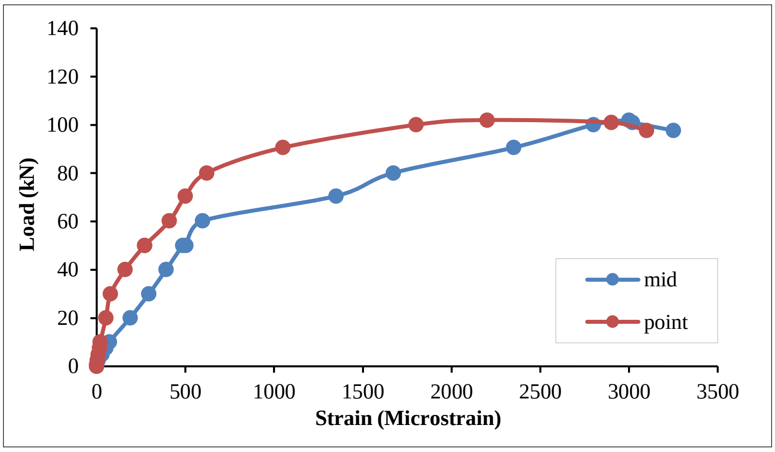
(c) Load-concrete strain curves of B-S40.



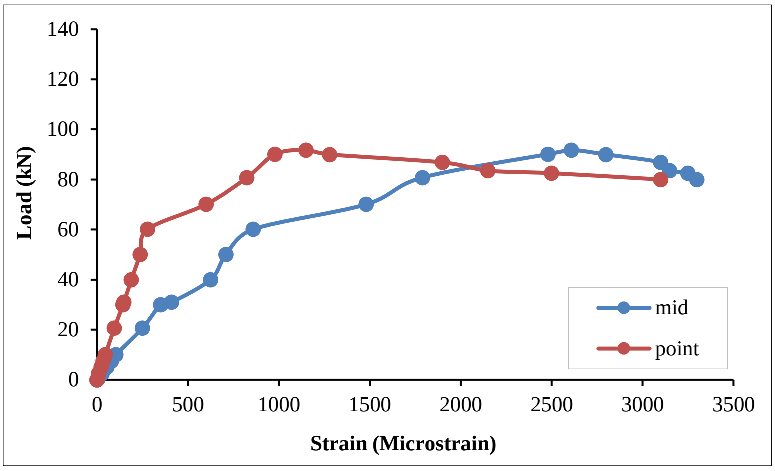
(d) Load-concrete strain curves of B-S60.



(e) Load-concrete strain curves of B-S20-T1.5.



(f) Load-concrete strain curves of B-S40-T1.5.



(g) Load-concrete strain curves of B-S60-T1.5.

Figure 4. Load-concrete strain curves

4. Conclusions

Based on the experimental findings of the study involving a vertical square opening with side lengths of 20 mm, 40 mm, and 60 mm positioned at the midspan of the beam and strengthened by reinforcing the opening using a 1.5 mm thick steel plate, several important conclusions can be drawn:

- Concrete openings inside RC beams reduce their performance by decreasing ultimate strength and increasing medium-range displacement. i.e., the size of a square vertical opening significantly impacts beam behavior, with larger openings (e.g., 60 mm, 50% reduction in beam width) resulting in reduced load capacity and strength compared to smaller openings (e.g., 20 mm). Within the range of openings considered in this study, vertical openings resulted in an average decrease of approximately 15-33% in ultimate load capacity.
- The presence of an opening leads to increased stress concentrations around it, making it a weak point where failure can occur if not properly reinforced.
- The size of a square vertical opening significantly affects beam behavior, with larger openings (such as 60 mm) resulting in reduced load capacity and strength compared to smaller openings (such as 20 mm).
- The improvement in load capacity using steel tubes with a thickness of 1.5 mm ranged between 11% and 13%.
- The reduction in deflection due to the presence of the opening was 23.14% for the B-S20 specimen, 41.77% for the B-S40 specimen, and 45.34% for the B-S60 specimen. In comparison, reinforcement with a 1.5 mm thick steel tube resulted in an increase in deflection, with values of 18.79% for the B-S20-T1.5 specimen, 12.40% for the B-S40-T1.5 specimen, and 3.55% for the B-S60-T1.5 specimen.
- The increase in steel strain for specimens without reinforcement ranged from 25% to 30% compared to the reference specimen. For specimens reinforced with a 1.5 mm thick steel tube, the increase ranged from 28% to 31% compared to the reference specimen.
- It was revealed that the strain on the concrete at the mid-span adjacent to the opening consistently exceeded the strain observed away from the opening, with an increase ranging from 3% to 22%. Furthermore, higher strain levels were observed on the concrete in samples with openings compared to the reference beam, with increases ranging from 5% to 12% for gauges near the opening and 10% to 20% for gauges positioned away from the opening.
- Testing appropriate beam dimensions and providing adequate reinforcement are crucial for structural safety and load capacity, as based on the findings of this study.
- The study suggests practical guidelines for designing beams with vertical openings, focusing on selecting appropriate opening sizes and reinforcement techniques to ensure safety and structural performance.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A.S. and A.F.I.; methodology, M.A.S. and A.F.I.; investigation, M.A.S. and A.F.I.; writing—original draft preparation, M.A.S. and A.F.I.; writing—review and editing, M.A.S. and A.F.I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Hamid, N. A. A., Salleh, N., Ali, N., Abdullah, S. R., Adnan, S. H., & Jamellodin, Z. (2022). Strengthening of Reinforced Concrete Beams with Circular Opening at Flexure Zone by Various Types of Fiber Reinforced Polymer. IOP Conference Series: Earth and Environmental Science, 1022(1). doi:10.1088/1755-1315/1022/1/012053.

[2] Ame, F. El, Mwero, J. N., & Kabubo, C. K. (2020). Openings Effect on the Performance of Reinforced Concrete Beams Loaded in Bending and Shear. Engineering, Technology & Applied Science Research, 10(2), 5352–5360. doi:10.48084/etasr.3317.

[3] Mansur, M. A., & Tan, K. H. (1999). Concrete beams with openings: analysis and design. CRC Press, Boca Raton, United States.

[4] ACI 314R-16. (2016). Guide to Simplified Design for Reinforced Concrete Buildings. American Concrete Institute, Michigan, United States.

[5] Morsy, A. M., & Barima, A. M. (2019). Behavior of R.C. Beams with Openings using Different Strengthening Techniques. International Journal of Sciences: Basic and Applied Research, 46(1), 195–219.

[6] Olanitori, L. M., & Tifase, T. O. (2019). Effect of small transverse service holes on shear strength of reinforced concrete slender beams. Journal of Applied Sciences and Environmental Management, 23(3), 539. doi:10.4314/jasem.v23i3.25.

[7] Chin, S. C., & Doh, S. I. (2015). Behaviour of reinforced concrete deep beams with openings in the shear zones. Journal of Engineering and Technology (JET), 6(1), 60-71.

[8] Elsayed, M., Badawy, S., Tayeh, B. A., Elymany, M., Salem, M., & ElGawady, M. (2022). Shear behaviour of ultra-high performance concrete beams with openings. Structures, 43, 546–558. doi:10.1016/j.istruc.2022.06.071.

[9] Ling, J. H., Ngu, J. T. S., Lim, Y. T., Leong, W. K., & Sia, H. T. (2022). Experimental Study of RC Hollow Beams with Embedded PVC Pipes. Journal of Advanced Civil and Environmental Engineering, 5(1), 11. doi:10.30659/jacee.5.1.11-23.

[10] Shaheen, Y. B., Eltaly, B. A., Yousef, S. G., & Fayed, S. (2023). Structural Performance of Ferrocement Beams Incorporating Longitudinal Hole Filled with Lightweight Concrete. International Journal of Concrete Structures and Materials, 17(1), 21. doi:10.1186/s40069-023-00579-3.

[11] Aziz, A. H. (2016). Experimental and Theoretical Evaluation for Effect of Openings Location on Shear Strength of RC Beams. Journal of Engineering and Sustainable Development, 20(1), 1-15.

[12] Hassan, S. A., Hemzah, S. A., & Alyhya, W. S. (2020). Experimental investigation of the structural behaviours of self-compacted reinforced concrete hollow beams with in-place circular openings. IOP Conference Series: Materials Science and Engineering, 671(1), 012117. doi:10.1088/1757-899x/671/1/012117.

[13] Abdel-Kareem, A. H., & El-Azab, I. A. (2019). Behavior of Concrete Deep Beam Reinforced with Inclined Web Reinforcement around Different Opening Shapes. Advances in Research, 20(3), 1–12. doi:10.9734/air/2019/v20i330158.

[14] Alshimmeri, A. J. H., & Al-Maliki, H. N. G. (2023). Structural Behavior of Reinforced Concrete Hollow Beams under Partial Uniformly Distributed Load. Journal of Engineering, 20(07), 130–145. doi:10.31026/j.eng.2014.07.09.

[15] Sathiyapriya, D., Suganya Devi, K., & Sattainathan Sharma, A. (2021). Study on Flexural Behaviour of Reinforced Concrete Beam with Effective Openings. Journal of Physics: Conference Series, 2040(1), 012030. doi:10.1088/1742-6596/2040/1/012030.

[16] Badawi, A. K., Yahia, Y. I. O., & Abdulla, A. I. (2023). Structural Behavior of Hollow Beam Reinforced with Different Types of GFRP Stirrups. Tikrit Journal of Engineering Sciences, 30(1), 72–83. doi:10.25130/tjes.30.1.7.

[17] Mohammed, T. A., & Alebachew, T. (2022). Numerical Investigation of As-Built and Carbon Fiber Reinforced Polymer Retrofitted Reinforced Concrete Beam With Web Openings Under Impact Loading. ASEAN Engineering Journal, 12(1), 173–182. doi:10.11113/AEJ.V12.17521.

[18] Rahimi, S. B., Jalali, A., Mirhoseini, S. M., & Zeighami, E. (2021). Experimental comparison of different types of frp wrapping in repairing of RC deep beams with circular openings. International Journal of Engineering, 34(8), 1961-1973. doi:10.5829/ije.2021.34.08b.17.

[19] Saleem Abdul-Razzaq, K., Ali, H. I., & Abdul-Kareem, M. M. (2017). A new strengthening technique for deep beam openings using steel plates. International Journal of Applied Engineering Research, 12(24), 15935–15947.

[20] Abdul-Razzaq, K. S., & Abdul-Kareem, M. M. (2018). Innovative use of steel plates to strengthen flange openings in reinforced concrete T-beams. Structures, 16, 269–287. doi:10.1016/j.istruc.2018.10.005.

[21] Rahmani, Z., Naghipour, M., & Nematzadeh, M. (2019). Flexural performance of high-strength prestressed concrete-encased concrete-filled steel tube sections. International Journal of Engineering, 32(9), 1238-1247. doi:10.5829/ije.2019.32.09c.03.

[22] Silva, R. J. C., Pontes, A. E. de A., & Silva, R. F. da. (2016). Experimental Analysis of Reinforced Concrete Beams with Vertical Holes. South American Journal of Structural Engineering, 13(1), 3751. doi:10.5335/rsee.v13i1.3751.

[23] Paul, P. M., & Auta, S. M. (2021). Effect of Strengthening Vertical Circular Openings with Various Materials on the Behaviour of Reinforced Concrete Beams. Proceedings of the 1st NSE Minna Branch Engineering Conference: Role of Engineering in Sustainable Development Goals, 7-8 July, Minna, Nigeria.

[24] Ali, H. H., & Said, A. I. (2023). Experimental Study on the Performance of Concrete Beams Including Holes Reinforced with Glass Fiber Polymer. E3S Web of Conferences, 427, 02010. doi:10.1051/e3sconf/202342702010.

[25] Mohammed, M. Y., Ali, A. Y., Kadhim, M. M. A., & Jawdhari, A. (2024). RC Deep Beams with Vertical Openings: Behavior and Proposed Mitigation Techniques. Practice Periodical on Structural Design and Construction, 29(1), 4023060. doi:10.1061/PPSCFX.SCENG-1328.

[26] Mahuta, A. S., Oladipo, J., & Bala, A. (2021). Effect of vertical circular openings on flexural strength of reinforced concrete beam. Magazine of Civil Engineering, 6 (106), 10601. (In Russian).

[27] IQS 5/2019. (2019). IQS 5/2019, for Portland cement. Iraqi Standard, Baghdad, Iraq.

[28] IQS 45/1984. (1984). IQS 45/1984, for Aggregates of Natural Resources used for Concrete and Construction. Iraqi Standard, Baghdad, Iraq.

[29] ASTM 370-24. (2024). Standard Test Methods and Definitions for Mechanical Testing of Steel Products. ASTM International, Pennsylvania, United States. doi:10.1520/A0370-24.

[30] ASTM A615/A615M-20. (2022). Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. ASTM International, Pennsylvania, United States. doi:10.1520/A0615_A0615M-20.

[31] ASTM A496/A496M-07. (2013). Standard Specification for Steel Wire, Deformed. For Concrete Reinforcement. ASTM International, Pennsylvania, United States.

[32] Hashim, A. M., & Ali, A. Y. (2022). Structural Behavior of Reinforced Concrete Horizontally Curved Box Beam with Opening. International Journal of Engineering, 35(4), 774–783. doi:10.5829/ije.2022.35.04a.17.