Strengthening Reinforced Concrete Beams with Vertical Perforations by using Steel-Plate Tubing

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ABSTRACT

This study aimed to experimentally compare the bending behavior of reinforced concrete beams in the midspan zone of the maximum bending region with and without vertically perforated openings. Five rectangular cross-section beams were produced for this purpose: one solid specimen, one with an opening without reinforcing steel, and the remaining three had openings reinforced with steel tubes of thickness 1, 1.5, and 2 mm. The square opening width was 40 mm. All specimens were tested under a symmetric four-point loading until failure. The test results showed that all specimens failed in bending. The presence of an opening negatively affects the ultimate load-bearing capacity and bending. However, the bending behavior of the reinforced concrete beams exhibited superior performance as the thickness of the steel tube increased. Additionally, the maximum load-bearing capacity increased with increasing tube thickness.

Keywords-flexure; openings; reinforced concrete beams; steel tube

I. INTRODUCTION

In contemporary building construction, numerous pipes and ducts are essential for key services such as water, electricity, and telecommunications. These utility pipes allow designers to use the space above the beams, reducing the overall building height [1]. However, cutting holes in Reinforced Concrete (RC) beams can weaken them, affecting their capacity and stiffness. This reduced stiffness can lead to significant displacements under service loads, causing internal forces and moments to be redistributed along altered load paths. Although many studies have examined the effects of horizontal openings, less is known about vertical openings [2]. Adding openings to beams concentrates stress on their corners, leading to extensive cracking, which is aesthetically and structurally unacceptable [3]. Consequently, beams with openings become less rigid and experience excessive deflections under load. Specific design considerations are needed to manage crack widths and avoid early failure.

Openings in beams reduce their cross-sectional area, affecting overall stiffness and performance [4]. In recent decades, several experimental studies have investigated how transverse openings in beams affect them, exploring variations in both shape and size [5-10]. The location of the openings has also received significant attention [11-13]. Studies have explored the performance of RC beams with different openings through numerical simulations and finite element analysis [14-17]. A significant drawback of these openings is the decrease in beam stiffness, which results in higher deflection and disrupts the natural stress distribution, leading to stress concentration and early cracking. Various solutions have been proposed to address these challenges. Additional reinforcing steel has been proposed [18-20], along with the utilization of Glass Fiber Reinforced Polymer (GFRP) for strengthening purposes [21, 22], which has shown effectiveness in reducing midspan deflection and enhancing resistance against brittle failure. Furthermore, the use of steel plates in the strengthening process has shown promising results in significantly improving strength and reducing average deflection [23, 24].

Although the topic has been extensively researched, few experimental studies have examined the bending characteristics of reinforced beams with vertical openings [25-31]. In [30], it was examined how reinforced concrete T-beams are affected by vertical openings or cold joints in the flanges. Eight beams were tested, including one without openings for comparison. This study specifically focused on how the position of these openings or joints affects the shear behavior. The T-beams were supported at both ends and tested with a single-point load to failure, without using shear reinforcement (stirrups). The results showed that the flange openings reduced the shear capacity by 22 to 32% for beams with a single opening and by

17% to 39% for those with two openings. Beams with cold joints experienced a 27% reduction in shear capacity compared to the reference beam. This study controlled different factors such as span, cross-section, concrete strength, and reinforcement.

In [31], experiments were carried out to study how openings affect the shear response of RC beams. This study aimed to investigate how vertical openings affect the strength and behavior of simply supported beams. Five beams were tested, one without an opening as a reference and the others with a mid-shear span opening. This study examined opening direction, shape, and how reinforcement affected openings. The results indicated that having a vertical opening led to a slight reduction in the ultimate load capacity and had a negligible effect on increasing the deflection. Circular openings had a smaller impact on reducing load capacity compared to square ones. The use of stirrups on both sides of the opening along its length proved effective in enhancing the ductility and recovering the lost strength. Interestingly, lateral openings had a more substantial impact on ultimate load compared to vertical openings.

This study aims to bridge this knowledge gap by evaluating and improving our understanding of how RC beams behave when they have vertical openings that span the entire depth and obstruct reinforcement bars, considering the effect of different thicknesses of steel tubes. The significance of this study is highlighted by the absence of research and publications on this topic.

II. EXPERIMENTAL PROGRAM

Five RC beams were constructed and tested. One of the beams was tested without any openings, while the remaining four contained square openings with a width of 40 mm. Among these beams with openings, three had steel tubes with varying thicknesses and one did not have a steel tube.

A. Material Properties

All beams used in the testing were prepared simultaneously and cured under identical conditions to ensure consistent compressive strength. Ordinary Portland cement was used along with sand (maximum size 4.75 mm) and gravel (maximum size 14 mm) to cast all specimens. 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 42.81 MPa. Direct tensile tests were performed on reinforcing steel bars with a specific diameter Ø12 mm and Ø6 mm. Yield strength was measured at 600.79 MPa for Ø12 mm steel bars and 476.8 MPa for Ø6 mm steel bars. Tensile tests were also performed on various steel tube specimens. The yield strength results were 482.96 MPa for tubes with a 1 mm thickness, 477.5 MPa for 1.5 mm thickness, and 454.83 MPa for 2 mm thickness.

B. Specimen Details

The beams share a cross-sectional dimension of 180×120 mm and a length of 1400 mm. The tests involved two-point loads applied with a total span of 1200 mm and a central load distance of 300 mm. To ensure that the beams fail in bending, they were reinforced with additional longitudinal and shear reinforcement, including 2 Ø12 mm deformed bars at the bottom. Steel stirrups were placed in the shear span to prevent failure, starting 40 mm before the support face and continuing at 75 mm intervals for a total distance of 560 mm from the support face. This configuration allowed for a midspan opening of 80 mm, where 40 mm diameter holes could be placed with a 20 mm concrete cover. Additionally, top reinforcement in the form of Ø6 mm steel deformed bars was employed to anchor the stirrups. Each beam had a 40 mm opening. Figure 1 shows the specific layout of the beam tests. To ensure that the description of each beam is easily identifiable, each beam was assigned a designation based on its variables, whether it was solid or had an opening, and the description of the steel tube thickness. Figure 2 shows the layout and definition of the specimen naming convention. Table I presents an overview of the tested beams, including their descriptions and details.

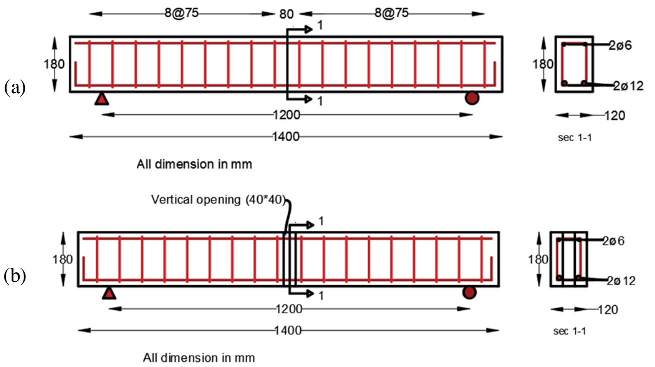

Fig. 1. Geometric and reinforcement details (side view): (a) reference beam, (b) beam with square opening.

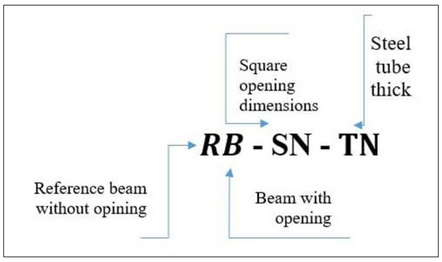

Fig. 2. The specimen naming convention and its arrangement.

TABLE I. DETAILS OF THE TESTED BEAMS

No	Specimen designation	Steel tube thickness (mm)	Opening width (mm)
1	R-solid	-	-
2	B-S40	-	40
3	B-S40-T1.0	1.0	40
4	B-S40-T1.5	1.5	40
5	B-S40-T2.0	2.0	40

C. Test Setup

All beams were loaded at two points until failure using a hydraulic testing machine capable of handling loads up to 1000 kN. The specimens were supported at one end on a roller and at the other end on a hinge. A spreader steel beam was used to apply the load to the tested beam. Bearing plates, measuring 120×75×8 mm, were placed on supports and loading points to prevent local crushing of the concrete. To measure the deflection of the tested beams, Linear Variable Differential Transformers (LVDTs) were installed vertically at the midspan section. These LVDTs provided precise displacement measurements, which were recorded by a computer program in an Excel sheet during testing. Each LVDT had an accuracy of 0.001 mm and a stroke of 100 mm. The load was applied step by step using a load control method at a rate of 0.1 kN/s. The cracks that developed on the concrete beams were marked with a heavy felt pen to aid in positioning and identifying the cracks during and after the test. Figure 3 shows the arrangement of the beam test.

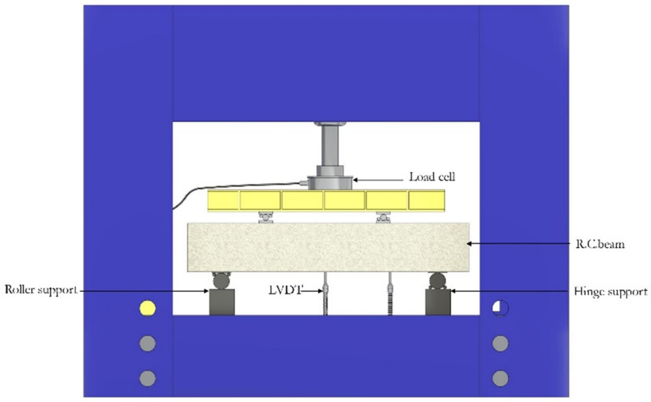

Fig. 3. Test rig.

III. RESULTS AND DISCUSSION

This study aimed to investigate the impact of vertical square openings on the strength of RC beams and determine the impact of reinforcing these openings with steel plates of varying thicknesses. This study aimed to find methods to restore the lost beam strength caused by the presence of the opening.

A. *Ultimate Loads*

As shown in Table II, the load-bearing beams demonstrate a reduced load capacity when openings are present. Specifically, for beam B-S40, the load capacity shows a decrease of 24.2% compared to the ultimate load of the reference beam. This observation is consistent with the findings reported in [8]. The reduction in load capacity is due to the decreased concrete area, which limits the full development of compressive stress blocks at the ultimate load. From Table II and Figure 4, it becomes apparent that the load increases gradually compared to the ultimate load of beam B-S40. The load capacity increases by 10.01% for sample B-S40-T1, 12.21% for sample B-S40-T1.5, and 23.21% for sample B-S40-T2. These findings establish a distinct association between the thickness of the steel plates and the applied load. Notably, as the thickness of the steel plates increases, there is a concurrent increase in the applied load, underscoring a proportional correlation between these two factors. The reason for this is that the material's resistance to bending increases when the thickness is larger. In other words, the thicker the pipe, the more it can withstand the pressure and forces acting on it. This makes it stronger and more durable, thus increasing the strength of the beam. These findings align with the results obtained in [23, 26].

TABLE II. ULTIMATE LOAD CAPACITY AND DEFLECTION AT MIDSPAN

Specimens	**Ultimate load (KN)**	**Increase in ultimate load (%)***	**Reduction in ultimate load (%)****	**Deflection at ultimate load, δu (mm)**
R-Solid	120	-	-	12.88
B-S40	90.9	-	24.2	7.5
B-S40-T1.0	100	10.01	-	12
B-S40-T1.5	102	12.21	-	8.43
B-S40-T2.0	112	23.21	-	9.87

* Increase in ultimate load compared to B-S40.

**Reduction in ultimate load compared to R-Solid.

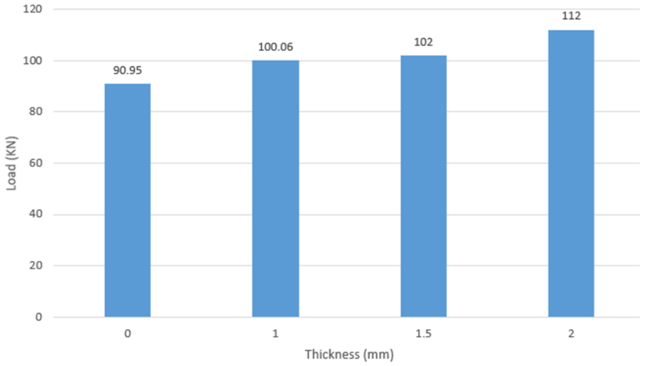

Fig. 4. Load-thickness relationship chart.

B. *Cracking Behavior*

At the onset of loading, the RC beams exhibit a crack-free state. As the applied load increases, exceeding the concrete's tensile strength, cracks are initiated from the tensile portion of the cross-section. Typically, the first crack manifests itself as a vertical flexural crack within the pure bending zone. Insights into crack initiation are provided by the experimental findings detailed in Table III. The B-S40 beam experienced a 15.34% load reduction at first cracking compared to the reference beam. Additionally, an increase in steel plate thickness resulted in a decrease in the percentage reduction of the cracking load. This means that thicker steel plates improve the beam's ability to withstand higher loads before reaching the point of cracking. Therefore, increasing the steel plate thickness improves overall structural performance by delaying the onset of significant damage and enhancing the load-bearing capacity. The percentage reductions in the first cracking load for samples B-S40-T1, B-S40-T1.5, and B-S40-T2 were 13.86%, 13.36%, and 11.38%, respectively.

During crack formation, cracks appear sporadically, initially vertical and concentrated in the central zone before extending to the shear span. As loading intensifies, additional inclined cracks emerge due to shear forces, termed web-shear cracks. As shown in Figure 5, the diagonal cracks for only R-Solid B-S40-T2 specimens propagated toward the nearest concentrated load and penetrated the concrete compression zones at the loading point, which is due to their higher load capacity. On the other hand, due to the reduced load-bearing capacity of the B-S40 specimen, it exhibited the fewest cracks. In general, it can be observed that cracks increase in the vicinity of the opening due to high stress concentration.

TABLE III. ULTIMATE LOAD - EXPERIMENTAL FIRST CRACKING LOAD

Specimens	First cracking load (KN)	Reduction in cracking load (%)
R-Solid	20.2	-
B-S40	17.1	15.34
B-S40-T1	17.4	13.86
B-S40-T1.5	17.5	13.36
B-S40-T2	17.9	11.38

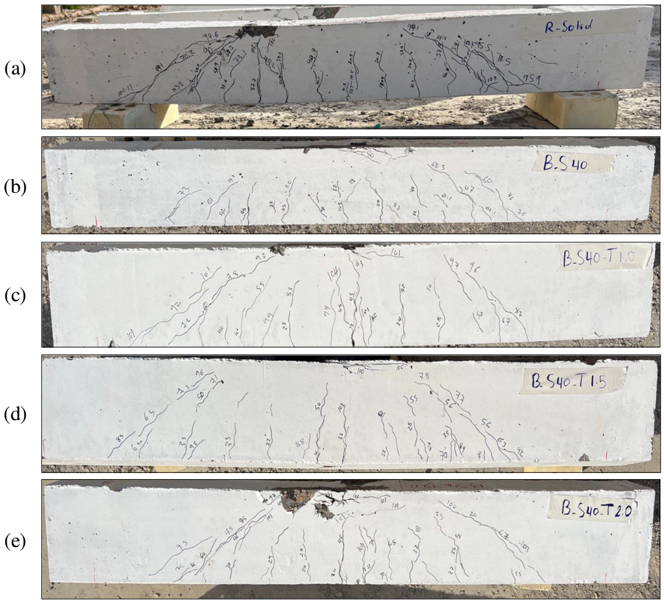

Fig. 5. Crack patterns at failure for (side view) (a) R-solid specimen, (b) B-S40 specimen, (c) B-S40-T1 specimen, (d) B-S40-T1.5 specimen, (e) B-S40-T2 specimen.

C. *Modes of Failure*

As mentioned before, the reinforced concrete beams were intended to fail due to flexural tension. This type of failure was consistently observed during testing, marked by the yielding of the main reinforcement bars followed by concrete crushing. It's noteworthy that the deflection at the midspan increased rapidly, leading to concrete crushing at the central zone on top of the beam. In the case of the reference beam, failure occurred near the midspan, while for beams with vertical openings, failure occurred at the opening section, as shown in Figure 6 (a). On the other hand, the use of steel plates caused cracks to form around the opening. As failure occurred, the cracks widened, resulting in the concrete surface separating from the steel plates, as shown in Figure 6 (b), (c), and (d).

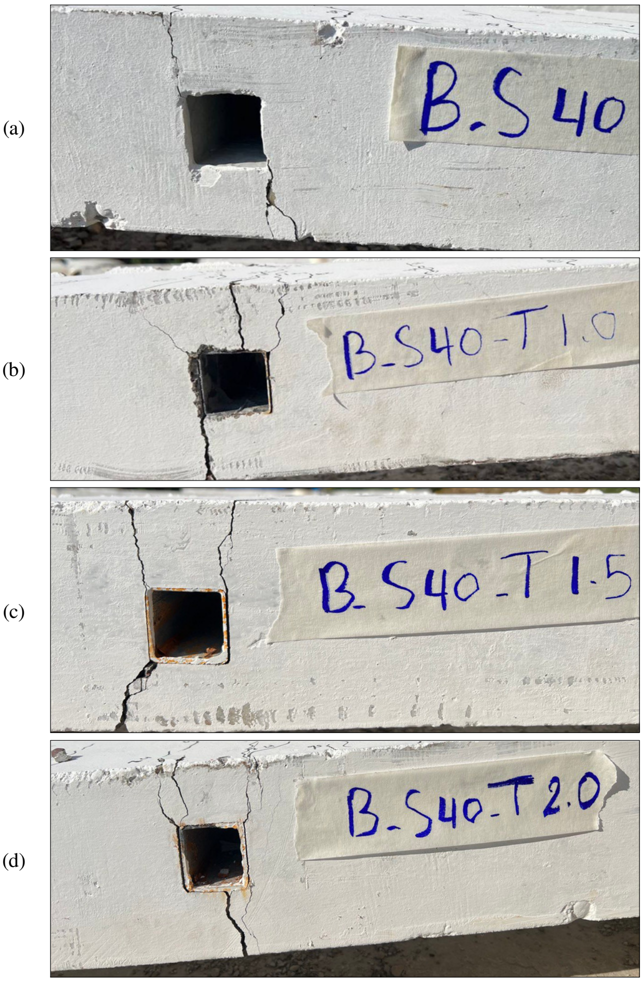

Fig. 6. Specimens failing at vertical openings (bottom view): (a) B-S40, (b) B-S40-T1.0, (c) B-S40-T1.5, (d) B-S40-T2.

D. *Load-Deflection Relation*

Figure 7 shows the correlation between load and midspan deflection.

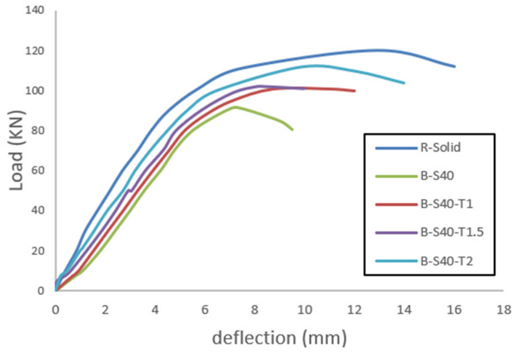

Fig. 7. Load-deflection curves at midspan.

The reference beam (R-Solid) demonstrated superior load-bearing and deflection characteristics compared to beams with openings due to its continuous structure. The load-deflection curves for beam B-S40 consistently showed decreasing load capacity and increasing deflection rates after initial cracking, particularly affected by the presence of openings. This result is consistent with the findings in [32]. The addition of steel plates enhances the stiffness and strength of concrete beams. It can be observed that with a constant opening width of 40 mm, the strength and stiffness increase with the thickness of the steel plate. Integrating steel plates within the openings improves beam strength and stiffness, partially compensating for the negative effects of the openings.

IV. CONCLUSION

Drawing from the experimental findings of the study, which involved a vertical square opening with side lengths of 40 mm positioned at the midspan of the beam and reinforced using steel plates of varying thicknesses, several significant conclusions can be drawn:

- The presence of holes significantly affects the behavior of reinforced concrete beams, resulting in reduced ultimate load and increased midspan deflection.
- Within the range of openings considered in this study, it was observed that the presence of vertical openings resulted in an average decrease of approximately 24.2% in ultimate load capacity.
- The openings act as inherent weaknesses in the structure, making them critical failure points. Without additional reinforcement, the failure plane will consistently pass through these openings.
- This study elucidates a clear relationship between the beam's ultimate load, mid-span deflection, and the thickness of the reinforced steel plate. Increasing the steel plate thickness improves the beam's ultimate load-bearing capacity while reducing its deflection.

Specifically, with a thickness of 1 mm, the load increased by 10.01% compared to the B-S40 threshold. At 1.5 mm thickness, the increase was 12.21%, and at 2 mm thickness, it increased to 23.21%. In summary, this study underscores the intricate interplay between vertical square openings and the effectiveness of varying thickness reinforcement plates in improving beam behavior. It emphasizes the critical importance of deliberate design and reinforcement strategies to optimize the performance and durability of structural elements.

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