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Behavior of reinforced concrete beams with shear-span vertical openings at different positions

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Abstract

Vertical openings are often incorporated into Reinforced Concrete (RC) beams to accommodate various services and necessities. However, there is limited research concerning the optimal position to pass these openings along the beam's span. In this experimental study, four RC beams were tested under symmetric four-point bending to failure, one reference beam without an opening and three beams with vertical openings. The main parameters investigated were the presence of the opening and the effect of its specific position within the shear span. The results showed that the presence of vertical openings in the shear span caused a reduction in cracking load by 1.96-23.53%, ultimate load by 2.07-18.26%, and energy dissipation capacity (EDC) by 16.20-47.17%, with BC-SU which had an opening near the support exhibiting the least impactful effect, followed by BC which had an opening in the center of the shear span, while BC-LO which had an opening near the load point experiencing the highest reduction in strength and EDC, in addition to causing a failure mode change from flexure to shear.

1. Introduction

Vertical Openings are often needed in modern construction of concrete structures for the passage of various services such as water and sewage pipes, air-conditioning ducts, and ducts for electricity and networking wires. These openings are often chosen to be passed through the slab, due to its ability to redistribute the stresses avoiding stress concentration [1]. However, these conduits would appear to be esthetically displeasing and are often needed to be covered with false ceilings which reduces the floor height and wastes space. One of the solutions for this problem is to pass these conduits through the beam to conceal them. This, in turn, gives rise to the issue concerning the effect of these openings on the behavior of beams [2]. Establishing openings in existing reinforced concrete (RC) beams will alter the traditional path of stress, and results in a decrease in the capacity and a decrease in the stiffness of the beam, and a subsequent large redistribution of internal forces and moments [3, 4]. Aside from strength and load-carrying considerations, the presence of openings also affects serviceability, including deflection and crack width, as reported by Chin et al. [5].

The shear span in particular is often more adversely affected by the presence of openings due to the combined stresses of shear and bending that go through that region. Even small openings can cause a reduction in strength when placed in the shear span [6]. Moreover, the location of the opening throughout the shear span determines the extent of the disturbance to the stress paths and, by extension, the reduction in strength and serviceability, as web openings near the load are observed to affect beam performance more than web openings near the support, due to the shear concentration near the load [7, 8].

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The behavior of RC beams with web openings has been studied by many researchers. Ame et al. [9] investigated the effects of the size and elevation of openings on RC beams under combined bending and shear and found that larger openings below the centroid of the beam reduced the beam's strength the most while small openings above the centroid had the smallest effect. Chin & Doh [10] studied RC deep beams with shear-zone openings and noted significant reductions in shear capacity depending on proximity to the support. Aziz [11] examined the effect of different opening location on the shear strength of RC beams. It was found that openings near the middle of the shear span reduced the shear strength more than openings near the supports. Elsayed et al. [12] found that even in ultra-high-performance concrete, web openings in the shear zone caused significant strength reduction depending on the size and positioning of the opening.

Several experimental and numerical studies have examined the behavior of RC beams with vertical openings. Auta et al. [13] confirmed a decrease in flexural strength due to circular vertical openings in slender beams. A. Sayed [14] conducted a numerical study that showed that for beams with shear span openings, increasing the vertical opening's diameter caused a decrease in load capacity and in deflection at failure. It was also found that opening diameter had a larger effect than the number of openings. Silva et al. [15] showed that vertical openings, even outside of the shear zone, can cause substantial reduction in shear strength due to the diagonal tensile forces. Emara et al. [16] found that the existence of vertical openings in the shear zone of self-compacting concrete (SCC) or rubberized concrete (RUC) caused a decrease in load capacity, stiffness, and ductility, and increased mid span deflection at the ultimate load. Hamzah & Ali [17] found that vertical openings in the shear span caused slight reductions in ultimate load when compared to web openings and that the use of stirrups on both sides of the opening improved ductility and partially recovered lost strength.

Studies on strengthening beams with web openings have explored additional stirrups [18], fiber-reinforced polymer (FRP) wraps [19, 20], and steel plates [21, 22], and various combined techniques [23]. As for vertical openings, Al-Jazaeri & Dawood [24] showed that strengthening T-beams with vertical openings by using Carbon fiber reinforced polymer (CFRP) was extremely effective in restoring lost strength. Both Shneet & Izzet [25], and Khadhair & Izzet [26] tested steel tube strengthening's effectiveness inside vertical mid span openings and showed that increasing the steel tube's thickness improves the beam's load capacity and reduces deflection. Mohammed et al [27] investigated RC deep beams with vertical openings and deduced that, while using steel rebar mat was an effective strengthening method, replacing the opening vicinity with UHPC was more successful in recovering lost strength. Lastly, Nawar et al. [28] studied near-surface mounted (NSM) straight rods, both vertical and horizontal, NSM horizontal U-shaped rods, and cold-formed steel (CFS) plates as strengthening method for vertical openings in the shear span of RC beams, and found that CFS plates were the most effective form of strengthening.

Despite these efforts, the specific influence of opening location within the shear span on the capacity and failure mode of conventionally reinforced slender beams has not been sufficiently characterized, particularly for single-sided vertical openings. This study addresses this gap through an experimental program involving four simply supported RC beams, one solid and three with a vertical opening at different shear span locations, tested under symmetric four-point bending.

2. Experimental Program

Four RC beams were constructed and tested. One of the beams was tested without any openings and considered the reference beam, while the remaining three contained an opening with a diameter of 90 mm that ran vertically through the shear span. The variables were the presence of the opening, and the change in location of the opening throughout the shear span. The span, cross-section, concrete strength, and opening's size were kept constant for all tested specimens.

2.1. Material Properties

All tested beams were prepared simultaneously and cured under the same conditions to ensure consistent compressive strength. The specimens were cast with Ordinary Portland Cement (OPC), graded crushed gravel with a maximum size of 14 mm and natural sand with a maximum size of 4.75 mm. Table 1 shows the mixture proportions of the concrete mix. The cube compressive strength was obtained by testing three cubes with dimensions of 150 mm. The average compressive strength of concrete at 28 days was 42 MPa.

Table 1. Concrete mix design

Cement (kg)	Sand (kg)	Gravel (kg)	Water/Cement
400	700	1100	0.42

Deformed steel rebars were used for the main and additional reinforcement of the beams with diameters (Ø) of 10- and 16-mm. Tensile tests were conducted on samples obtained from each bar size, following ASTM A615/A615M-05a [29]. The properties of the bars are listed in Table 2.

Table 2. Mechanical properties of steel reinforcing bars

Diameter (mm)	Yield stress (MPa)	Tensile Strength (MPa)
10	597.5	673.4
16	643	715.6

2.2. Specimen Details

The aim of this experiment is to study the effect of vertical openings within the shear span on the behavior of RC beams. To achieve this, an experimental program was designed, consisting of four specimens of RC beams that were tested under four-point bending setup. All specimens had a rectangular cross-section with dimensions of 180 mm width and 280 mm depth, 20 mm cover, and 230 mm effective depth, with an effective span of 1900 mm and a total length of 2000 mm. The distance between the two points of loading is 500 mm and the shear span is 700 mm. These beam dimensions and loading configuration were chosen to have the specimens avoid entering the deep beam category, as the shear span to effective depth ratio was more than 2 (3.04), and the clear span was well over 4 times the total depth (6.78). All specimens were reinforced using four steel bars at the bottom with a diameter of 16 mm (4Ø16 mm) as the main longitudinal tension reinforcement which had hooks at the edges to avoid slippage between the rebars and the concrete, and two steel bars at the top with a diameter of 10 mm (2Ø10 mm) acting as the compression reinforcement, and the shear reinforcement of stirrups was Ø10@100 mm. Each beam; except the reference, contained a vertical opening that was established by using foam cylinders of 90 mm diameter at different positions within the shear span, these openings were fixed during the casting process by using wooden plates that were nailed to the sides of the molds to hold the foam cylinders in place, these cylinders were removed prior to beam testing by using a chemical solvent. Reinforcement and geometry details as well as the process of specimen's implementation are shown in Fig. 1 and Fig. 2, respectively. The ACI 314R-16's [30] Guide to Simplified Design limits opening diameter to one third of the width of the beam, however, for experimental purposes, an upper limit of 90 mm (50% of beam width) was applied to investigate the code limit.

Table 3 summarizes the beam opening configurations. In beams BC, BC-SU, and BC-LO, the vertical opening was introduced within one shear span only without intersecting stirrups, spanning the full 280 mm beam height on one face. The three opening positions represent near-support, mid-shear span, and near-load-point conditions respectively. The location of the openings was chosen to represent the most extreme cases as the closest to the support and the load point without applying the load directly to the opening. The 50 mm distance was due to the stirrup distribution.

Table 3. Opening configuration for the tested beams

Specimen	Opening Location
BR	None (Reference)
BC	Mid-shear span
BC-SU	50 mm from support
BC-LO	50 mm from load point

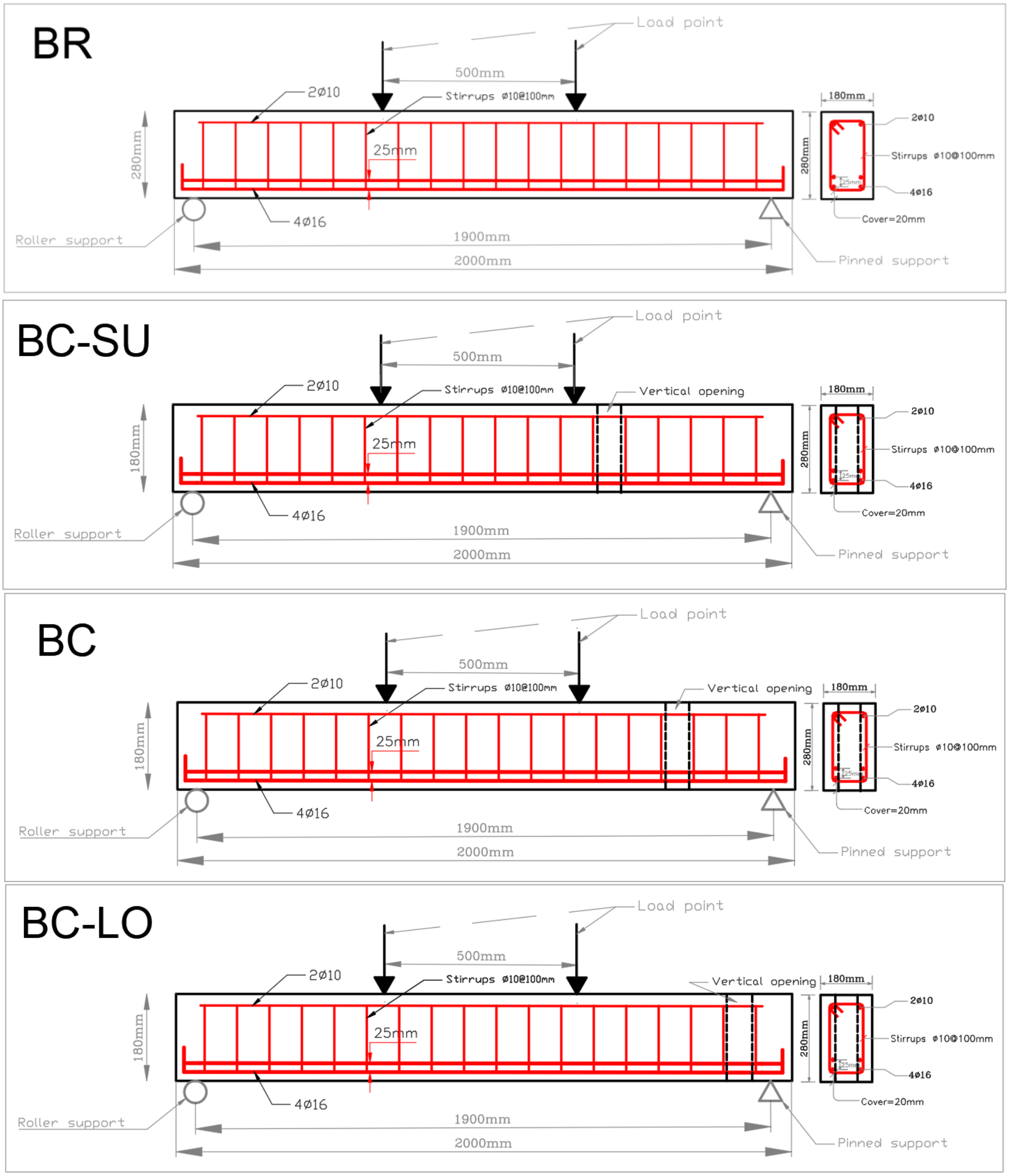


Fig. 1. Details of reinforcement and opening configuration for the tested beams

Fig. 2. Specimens Implementation

2.3. Test Setup

All beams were tested under symmetric four-point bending and were subjected to monotonic loading up to failure using a load control system. The beams were tested in a simply supported configuration, where one support allowed for horizontal movement and rotation, and the other allowed for rotation movement only. The test was carried out in the Structural Engineering Laboratory at the University of Baghdad.

A linear variable displacement transducer (LVDT) was set up to measure the mid span deflection of the tested beams, and a calibrated load cell was used to index the loads. A data logger was also used to automatically record all required data during the test, and the crack initiation and propagation were observed and marked with a permanent marker on the beam surface to track the development throughout the test.

3. Results and Discussion

3.1. Ultimate Load

As shown in Table 4, the beams demonstrate a reduced ultimate load capacity when openings are present when compared with the reference beam. Among the beams with openings, BC-SU performed closest to the reference, reaching 236 kN, a reduction of only 2.07%. This marginal reduction indicates that an opening near the support has a slight effect on the strength of the beam, where the compressive arch action may partially compensate for the sectional loss caused by the opening and with the absence of moment stresses which are more affected by the under-developed compressive stress block. This observation is consistent with the findings reported in [13]. Beam BC, with its opening at the mid-shear span, achieved an ultimate load of 225 kN, corresponding to a 6.64% reduction relative to BR. This moderate reduction reflects greater interference from the moment stress as the opening moves closer to the flexural zone. The most significant reduction was observed in BC-LO, which failed at 197 kN, an 18.26% reduction from BR. Placing the opening closer to the applied load causes a combination of shear and moment stresses to be applied to the opening section, as well as the stress concentration due to the applied load near the opening. These findings align with the results obtained in [15].

Table 4. Summary of experimental results

Specimen	Ultimate Load (kN)	Reduction vs BR (%)	Deflection at Ultimate load (mm)
BR	241	-	15.2
BC	225	6.64	11.0
BC-SU	236	2.07	13.1
BC-LO	197	18.26	10.5

3.2. Cracking Behavior

The opening location influenced both the magnitude and pattern of crack formation. Insights into crack initiations are provided in Table 5. The reference beam BR showed a first cracking load of 51 kN, the highest among all specimens. Beam BC-SU cracked at 50 kN, only 1.96% below BR, confirming that an opening near the support exerts minimal influence on the initial cracking formation. Beam BC cracked at 46 kN, a 9.80% reduction from BR, reflecting moderate stress concentration effects at the mid-shear span opening. The earliest cracking was observed in BC-LO at 39 kN, a 23.53% reduction compared to BR, indicating that the critical stress concentration induced by an opening adjacent to the loading point triggers early crack initiation in the high-shear zone.

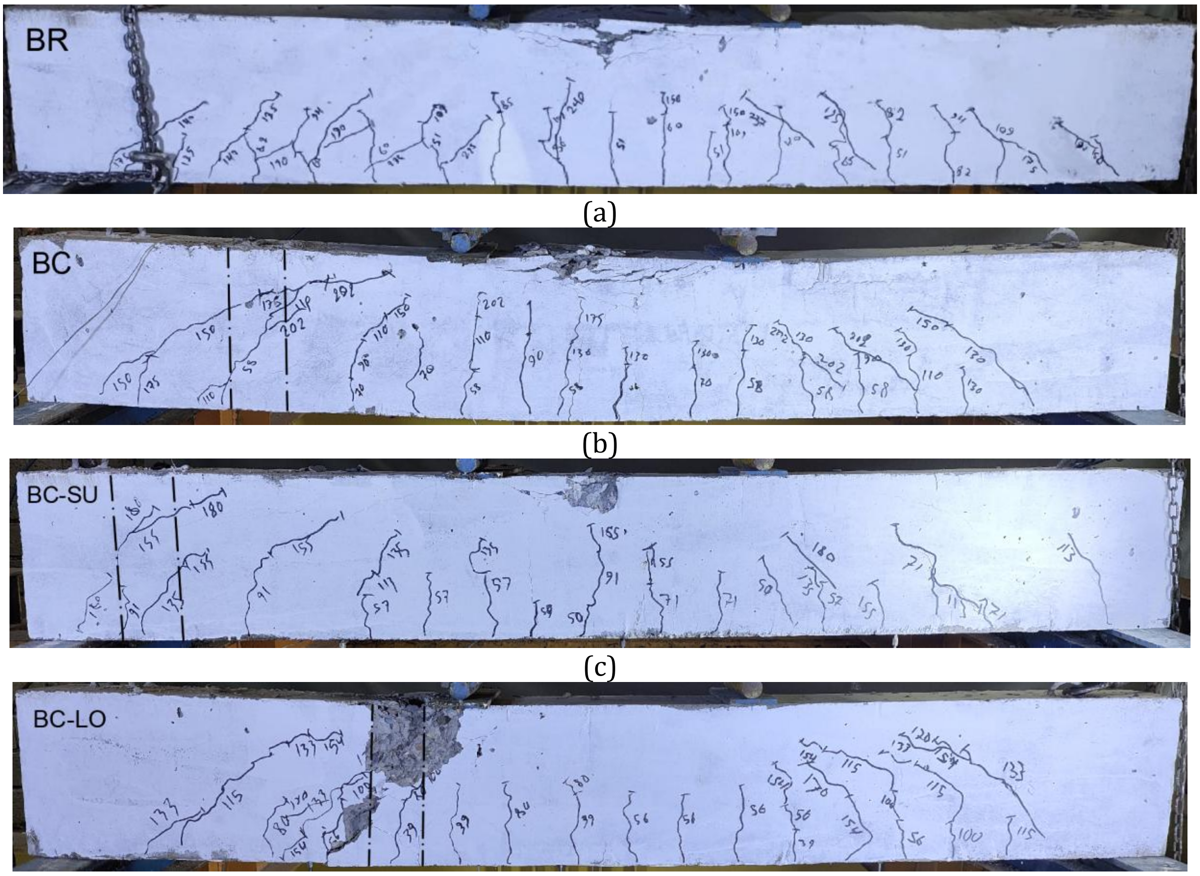
In all beams, the initial cracks appeared as vertical flexural cracks within the constant moment zone between the two load points. As loading increased, inclined flexural-shear cracks developed in the shear spans. In beams with openings, crack density was noticeably higher in the vicinity of the opening corners, consistent with the stress concentrations expected at opening corners [9,10]. In BC-LO, a dominant inclined crack rapidly widened across the critical shear section, accelerating the transition to the failure mode.

Table 5. Summary of experimental results

Specimen	First Crack Load (kN)	Reduction in First Crack Load vs BR (%)
BR	51	-
BC	46	9.80
BC-SU	50	1.96
BC-LO	39	23.53

3.3. Modes of Failure

Beams BR, BC, and BC-SU all failed in flexure. The reference beam BR developed extensive distributed flexural cracking throughout the constant moment zone, followed by yielding of the tensile reinforcement bars and eventual concrete crushing at the top fiber near midspan. Beams BC and BC-SU exhibited a similar failure progression, while experiencing additional crack formation in the opening vicinity, yet the predominant failure mechanism remained flexural, characterized by progressive crack opening, reinforcement yielding, and top fiber concrete crushing, as shown in Fig. 3 (a), (b), (c), and (d). In contrast with the other specimens, BC-LO exhibited a distinctly different and more brittle behavior. After the initial cracks in the constant-moment region, an inclined crack started forming between the load point going through the opening and to the far edge of the opening, as the loading increased the crack rapidly widened and a sudden failure occurred due to concrete fracture along the major crack combined with crushing in concrete at the upper tip of the opening. This failure occurred at an ultimate load of 197 kN, significantly lower than all other specimens and with considerably less midspan deflection at failure. This mechanism is consistent with conclusions reported in [27].



(a)

(b)

(c)

(d)

Fig. 3. Crack patterns and failure modes of all tested beams at ultimate load (a) Beam BR (b) Beam BC (c) Beam BC-SU (d) Beam BC-LO

The Strut-and-Tie action can also give insight into the failure mechanism of BC-LO. The three components of the Strut-and-Tie model are: compression struts, tension ties, and nodes that represents the intersection of struts and/or ties, as all the openings intersect both the strut and tie elements, the difference in behavior can be attributed to the proximity to the nodal zones, a simplified Strut-and-Tie model indicates the support point as a C-C-T node, while the load point as a C-C-C node. As the tie element is mainly resisted by the longitudinal reinforcement, this leaves the C-C-C node of the load point as the more vulnerable point, this and the immediate geometric discontinuity provided by the adjacent opening does not allow the redistribution of the stresses indicated by St. Venant's principle. Therefore, a nodal failure which propagated through the opening length occurred.

3.4. Load-Deflection Relation

Fig. 4 shows the load-deflection curves recorded for all four tested beams. In the pre-cracking stage, all beams exhibited comparable initial stiffness, with the four curves overlapping closely up to approximately 5 mm of deflection. This shows that vertical openings in the shear span had a negligible effect on the beam in the pre-cracking elastic behavior. Beyond this stage and entering the plastic behavior, the curves begin to diverge as each beam responds differently according to its respective internal damage state.

The reference beam BR reached an ultimate load of 241 kN at 15.2 mm midspan deflection while sustaining a remarkably long post-peak plateau, a behavior characteristic of a ductile flexural failure with progressive reinforcement yielding and gradual concrete crushing. Beam BC-SU exhibited a somewhat stiffer behavior than that of BR by undertaking the same load while experiencing less deflection until reaching loading values closer to its maximum where the increase in deflection starts to intensify before peaking at 236 kN with around 13.1 mm deflection before a gradual post-peak load decrease, confirming that an opening near the support causes little disruption to the over-all structural response.

Beam BC reached its ultimate load of 225 kN at a smaller deflection of approximately 11.0 mm, while exhibiting similar pre-failure behavior to BC-SU, this specimen experienced failure with a more abrupt post-peak descent compared to BR and BC-SU, reflecting a more sudden failure due to the mid-shear span opening.

Beam BC-LO showed the most brittle response: it peaked at 197 kN at approximately 10.5 mm deflection and exhibited a rapid, steep load drop immediately after the peak, characteristic of the sudden diagonal shear failure observed in this specimen. The sharply limited post-peak deformation capacity of BC-LO contrasts markedly with the extended plateau of BR, indicating the critical and dangerous influence of an opening positioned close to the load point on both load capacity and ductility.

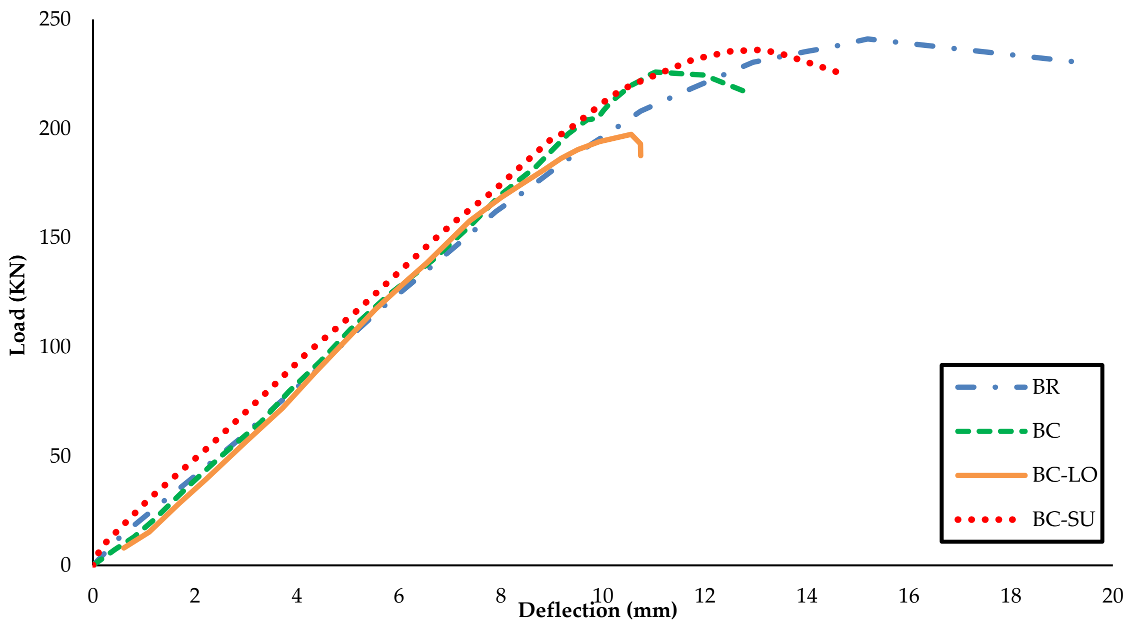


Fig. 4. Load-deflection curves for the tested beams

3.5. Energy Dissipation Capacity

Energy Dissipation Capacity (EDC) is the ability of a structure to endure plastic deformation without fracture by absorbing and dissipating energy, which is represented by the total area under the load-deflection curve from the start of loading up to the failure point, calculated using the trapezoidal numerical integration rule. It is considered an indication of the ductility of the beam. Fig. 5 shows the energy dissipation capacity for each specimen. Introducing an opening in the shear span caused a significant reduction in the EDC of the tested beams. BC-SU showed the mildest effect, experiencing a reduction of 16.20%. BC showed a significantly larger re-duction in EDC, showing a reduction of 41.89%. Lastly, BC-LO showed the largest reduction in EDC by 47.17%.

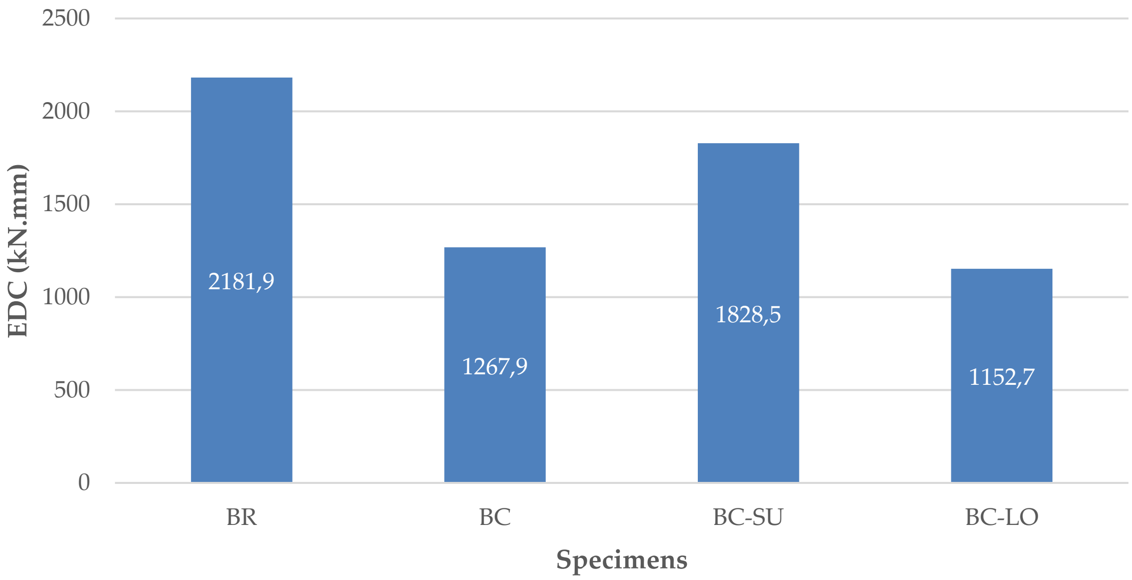


Fig. 5. Energy dissipation capacity of the tested beams

4. Conclusions

In this study, four simply supported Reinforced Concrete (RC) beams were tested under symmetric four-point bending. One beam served as a reference beam without an opening (BR), while the remaining three contained circular vertical openings of 90 mm diameter in different locations within the shear span. The following conclusions were derived from the experimental study:

- The presence of a vertical opening within the shear span reduces both the first cracking load and the ultimate load capacity, the magnitude of reduction varies greatly according to the opening's position within the shear span.
- An opening positioned 50 mm from the support face (BC-SU) had the least effect on structural performance of the beam, causing only 2.07% and 1.96% reductions in ultimate load and first cracking load, respectively, and an energy dissipation reduction of 16.20%. This gives an indication that the near-support region may benefit from compressive arch action that partially compensates for the presence of the opening.
- An opening at the mid-shear span (BC) caused a moderate 6.64% reduction in ultimate load and a 9.80% reduction in first cracking load, and a reduction of 41.89% in energy dissipation, while the failure mode remained flexural.
- An opening positioned 50 mm from the applied load point (BC-LO) caused the most severe effects: an 18.26% reduction in ultimate load, a 23.53% reduction in first cracking load, and a 47.17% reduction in energy dissipation. Most importantly, the failure mode changed from a ductile flexure failure to a brittle shear failure through the opening's length.
- All specimens failed in flexure except BC-LO. The change in failure mode in BC-LO can be attributed to the combination of flexural and shear stresses passing through that region and

concentrated stresses at the opening due to the applied load close by. While a strut-and-tie model may suggest the failure was initiated by a nodal failure at the load point.

- It is recommended that for this load configuration, when a vertical opening is needed to be placed within the shear span of RC beams, it should be placed as close to the supports as possible as it causes the least disturbance in the beam's behavior, while minding the stress concentrations.

Limitations of this study: the opening is a single circular opening of one diameter, the RC beam was set up as a normal strength, flexural-critical, slender beam.

Recommendation for future studies: different opening schemes (different shape, size and number) beams with shear-critical reinforcement, deep beams with vertical openings in the shear span.

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