Emerging Technologies and Engineering Journal

EngiScience Publisher

Review Article

Behavior of Reinforced Concrete Beams with Openings: A Review

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Article Info

Article History
Received Nov 21, 2024
Revised Jan 02, 2025
Accepted Jan 18, 2025

Keywords

Reinforced Concrete Beams
Opening Shape
Structural Behavior
Opening location
Load carrying capacity

Abstract

This paper reviews the effects of openings in reinforced concrete (RC) beams and their effects on the RC beams' ability to bear loads. RC beams may have openings due to the advancement of construction techniques and the rise of supplies and requirements during construction. The paper reviews the effects of opening sizes, locations, and shapes on the behavior of RC beams. It is found that the openings weaken the beam's overall resistance. Also, the openings in the shear zones have a bigger impact than the bending zones, making the beam more brittle during failure. Additionally, regarding the members' overall energy loss, circular openings are preferable over rectangular and square openings. It is also found that the beam's opening results result in shorter chord distances; therefore, rectangular openings work better horizontally than vertically to maintain a balance between compression and tension zones in the beam. Finally, the size of the openings inversely affects the strength and behavior of the RC beams.

1. Introduction

As technology progresses, the addition of various services like gas, electricity, water supply, and sewage to buildings creates openings in the beams. On the other hand, due to frequent earthquakes in various parts of the world, most designers have opted for the frame-building method as a preventive measure against earthquake damage. Hence, openings in beams have become inevitable despite their vulnerability to damage during earthquakes [1, 2].

The source of openings in RC beams in a building comes from decisions by the architectural and mechanical engineers' unambiguous height limitations. Structural engineers need to consider these openings during the design stage to allow for the passage of pipes, ducts, electrical wires, sewage pipelines, air conditioning outlets, telephone cables, plumbing, and internet connections [1-5]. Figure 1 illustrates RC beams with web openings.

Openings increase deflection crack size and decrease beam stiffness and capacity. Furthermore, the behavior of the beam changes from simple to complex behavior due to increased stress concentration at the opening cords, especially at the opening corners [3]. The beam might be strengthened to increase its load-carrying capacity and prolong its structural service life [4]. It is also proven that drilling openings in existing beams and their geometry significantly increase the vertical deflection of the beams while decreasing their flexural strength [5, 6]. Numerous issues arise when a beam's web has an opening, including decreased stiffness, excessive cracking, excessive bending, and decreased strength [7, 8]. It has been observed that the beam's structural reaction determines the opening's categorization; if the opening is sufficiently small to preserve the beam-type behavior, it may be referred to as a small opening. Large openings, on the other hand, are those that inhibit the development of beam-type behavior [9-11]. A square opening is deemed large when its height surpasses a quarter of the web's depth [12, 13], whereas a circular opening may be deemed large if its diameter surpasses 40% of the web's depth [14-16].

(a) Opening at shear region (b) Opening at flexure region

Figure 1. Different locations of openings in RC beams [1]

Numerous studies have been conducted to predict the load-deflection response, cracking, and final behavior of reinforced concrete beams with openings, and techniques for designing and analyzing these beams have been proposed [17-19]. For example, Somes and Corley [15] stated that a circular opening can be deemed significant if its diameter exceeds 0.25 times the web's depth since including such openings weakens the beam. According to their test results, the failure mechanism for a beam with a tiny opening in its web that is not reinforced in shear is nearly identical to that of a solid beam. However, according to Mansur [17], the failure plane always goes through the opening since it is a source of weakness, except when the opening is extremely near the support to avoid the possible inclined failure plane.

Openings significantly impact the beam's behavior when they are more than half the depth of the beam web. The existence of web openings can lower the members' bending and shear capacities and significantly impact the beams' strength and serviceability [19]. Additionally, when comparing beams with rectangular and circular openings to those with square openings, the ultimate load drop in the square openings was greater than beams with rectangular or circular openings [20].

Beam efficiency and structural safety become more complicated when openings are added. The size and placement of the openings influence the distribution of bending moments and shear force along the beam. Engineers are responsible for ensuring that the design adheres to applicable building rules and standards, maintains the necessary structural integrity, and handles any possible problems relating to stress concentrations [20].

A design methodology for RC beams with wide rectangular openings under point stresses was first presented by Mansur [17]. This strategy was extended to a technique to calculate the deflections of RC beams with huge rectangular openings. Their approach was predicated on the idea that a contra flexure point would arise in a Vierendeel mechanism in the middle of each chord. Ramadan, et al. [21] stated that the opening's depth ratio inversely affected the beam strength. Shifting toward the compressed side increases the impact of the opening presence, while shifting toward the tensioned side decreases it. Also, the reinforcement ratio substantially impacts the flexural behavior of beams with rectangular openings [22]. As the opening width and/or depth grow, the shear capacity decreases further [14].

This paper focuses on the behavior of the beam with openings, which summarizes the results of the published works by researchers who have conducted research studies to see how openings affect the behavior of beams in terms of resistance to flexure and shear forces, the type of failure, and the appearance of the first crack. Primarily, the paper emphasizes the effects of openings in different places and shapes, such as circular, rectangular, and square, on beams with specific dimensions from the width and depth of the section.

2. Effects of Opening Shapes and Orientations, Locations, and Sizes

Figure 2 presents the review details, focusing on three main variables: the effects of size, location, and shape of the opening on beam behavior.

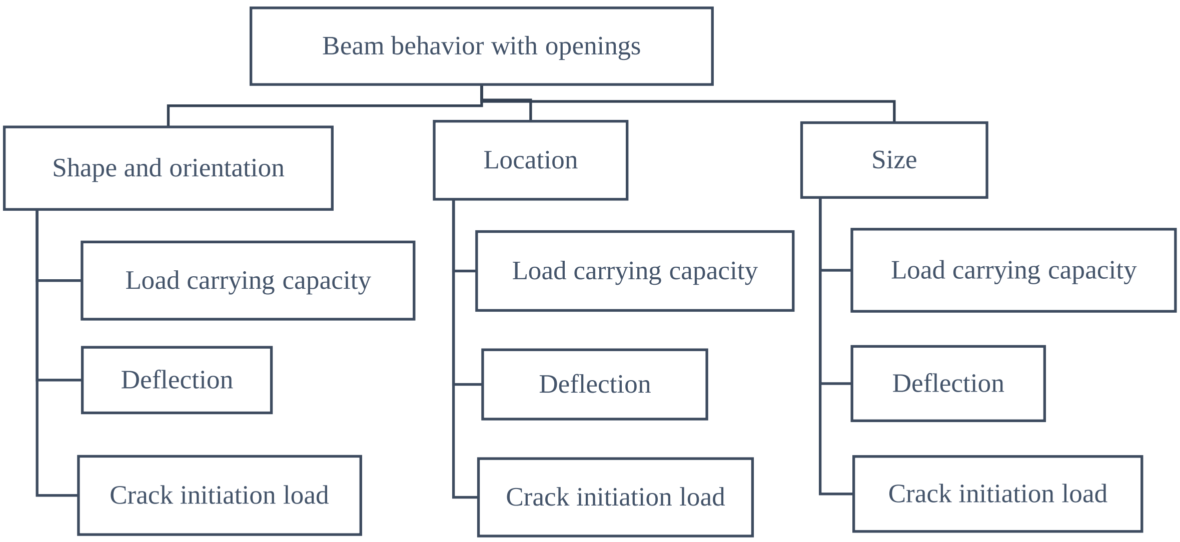

Figure 2. Summary of the work in this paper

Researchers have studied the behavior of beams with openings and the amount of load drop; this section provides a breakdown of the testing parameters they tested.

2.1. Effects of Shapes and Orientations of Openings

2.1.1. Load Carrying Capacity

Rectangular shapes have a greater impact on beam strength than circular ones [23-26]. Pimanmas [23] tested beams with cross-sections of 160 mm in width and 400 mm in height. 350 mm was the effective depth of the main reinforcement. Details of the beam sections are given in Figure 3. The setup consisted of nine beams designed to fail in a flexural mode. One beam was a control beam, and the remaining eight beams were split into two groups: the circular opening and the square opening, each consisting of four beams. The diameter of the circular opening was 150 mm, and the size of the square opening was 150 mm x 150 mm. The ratio of the opening size to the beam's effective depth was 0.43, which was large enough to reduce the shear capacity significantly. The opening was located precisely in the middle of the shear span, 525 mm from the support position.

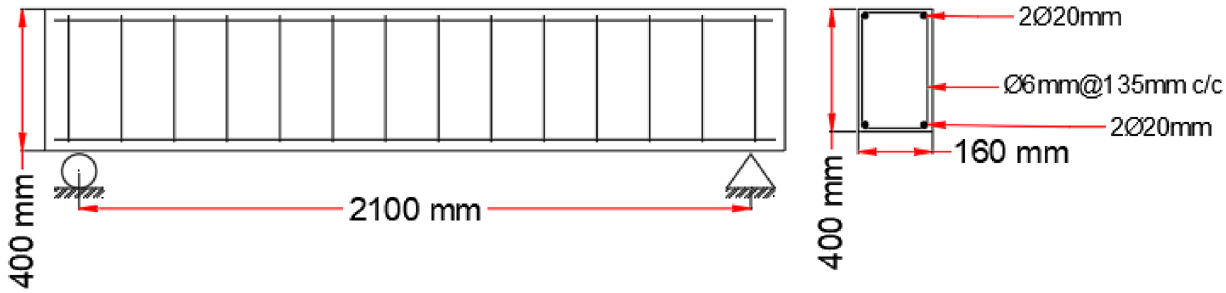

Figure 3. Beam span and cross-section with reinforcement [23]

Beams with square and circular openings had a load-carrying capacity ratio of 55.7% and 62.3%, respectively, compared to control beams. This indicates that the circular opening had less impact on the RC beams' load-carrying capacity than the square opening.

Also, Al-Sheikh [24] confirmed the same conclusions when they tested 27 beams, as shown in Figure 4. One beam was a control beam, and the other had an opening. Fourteen beams had circular openings in them; eight had diameters of 140 mm, 130 mm, 120 mm, 110 mm, 100 mm, 80 mm, 60 mm, and 40 mm in the shear region, and three had diameters of 140 mm, 80 mm, and 40 mm for both above the supports and in the flexure region. In each shear, nine beams with square openings of 125x125 mm², 80x80 mm², and 40x40 mm² dimensions, above supports and flexure regions, respectively. The final trio of beams featured rectangular openings measuring b = 140 mm and h = 80 mm in each shear, situated above the supports and flexure regions, respectively. According to the test results, a circular opening reduced the ultimate load by about 1%, a square opening reduced it by about 19%, and a rectangular opening reduced it by an average of about 23%.

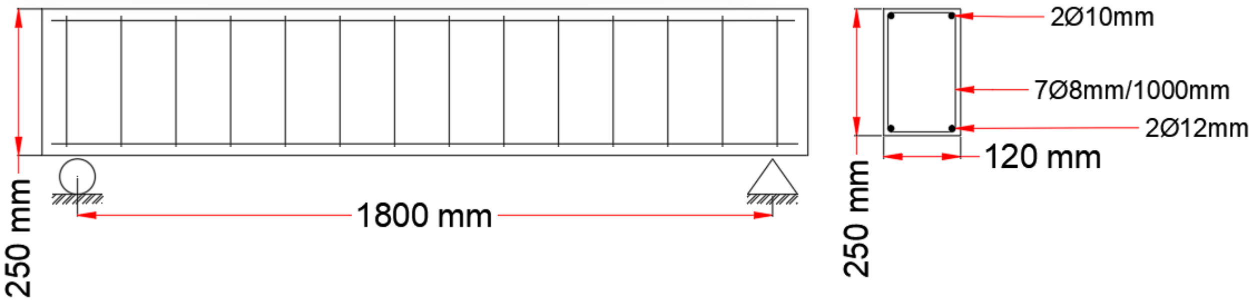

Figure 4. Beam span and cross-section with reinforcement [24]

Table 1 illustrates the opening shape, size, and location of specimens.

Table 1. illustrates the opening shape, size, and location

Shape	Shear zone	Over support	Flexure zone
Circular	140 mm, 130 mm, 120 mm, 110 mm, 100 mm, 80 mm, 60 mm and 40 mm	140, 80, and 40 mm	140, 80, and 40 mm
Square	125, 80, and 40 mm	125, 80, and 40 mm	125, 80, and 40 mm
Rectangular	(h=80*b=140) mm	(h=80*b=140) mm	(h=80*b=140) mm

The same conclusions were reached by Morsy and Barima [25] when they tested 24 half-scale beams, each measuring 1700 mm in length and 1500 mm in effective span, with a cross-section area width of 120 mm and a height of 300 mm, as shown in Figure 5. They focused on the shape and orientation of the openings, examining square, rectangular, and circular. The square openings measured 120 mm x 120 mm; the rectangular opening measured 98 mm x 147 mm with an aspect ratio of 1.5, and 85 mm x 170 mm with an aspect ratio of 2.0, and the circular opening measured 135 mm in diameter. The area of the openings was the same for all forms, measuring around 144 mm^3. Orienting the square opening from 90° to 45° "rhombus" did not significantly alter the shear or flexural zone; however, the advice is to make the rectangular opening horizontal rather than vertical. When comparing the various opening forms in both shear and flexure zones, the circular opening performed better, followed by the horizontal rectangular opening with an aspect ratio of 1.5, and the square openings performed the worst. Figure 5 shows the cross-section, reinforcement, and length of beams.

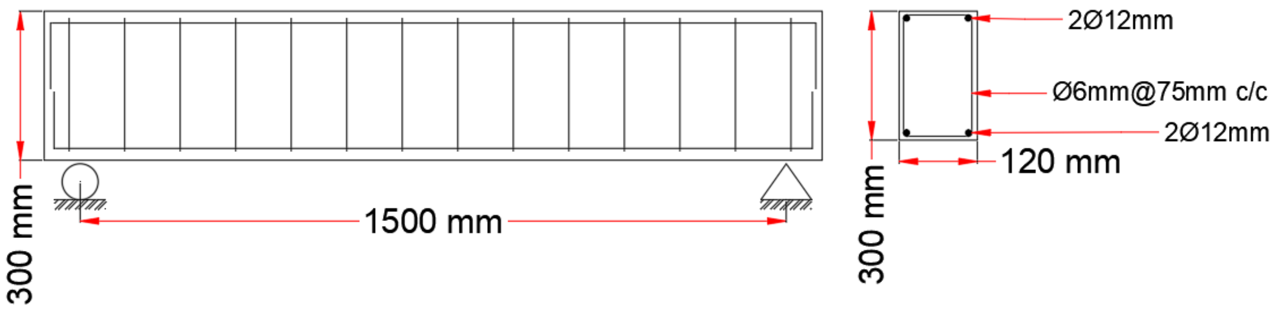

Figure 5. Beam span and cross-section with reinforcement [25]

Table 2 shows the opening dimension, shape, and orientation of the RC beams.

Table 2. Opening shape, dimension, and orientation

Shape	Dimension	Orientation
Square	120*120 mm	/
Square	120*120 mm	Rhombus- 45º
Rectangular	147*98 mm	Hz*
Rectangular	170*85 mm	Hz*
Rectangular	85*170 mm	Vt**
Circular	φ135 mm	/

*Hz = Horizontally. ** Vt = Vertically.

The load-carrying capacity ratio for different cases of opening shapes and their orientations concerning the load-carrying capacity of the control beam is shown in Table 3.

Table 3. The load-carrying capacity ratio for different cases of opening shapes and their orientations

Shape	Load carrying capacity ratio	Load carrying capacity ratio for oriented opening
Square	77%	64%
Square 45º	82%	73%
Rectangular Hz	79%	56%
Rectangular Hz	82%	65%
Rectangular Vt	82%	64%
Circular	91%	86%

A rectangular opening in the vertical direction performs worse than a similar opening in the horizontal direction; a square opening is the worst shape, lowering the load-carrying capacity by more than 23% compared to the control beam.

On the other hand, Hassan, et al. [26] tested thirteen beams under a single-point load in an experiment; one beam served as a control without an opening, while the other beams were created with an intended 100 mm x 200 mm opening that was positioned both vertically and horizontally in the web and had a center opening situated 550 mm from the end of the beams. Six had vertical openings positioned directly at the flange's bottom edge, as shown in Figure 6. The remaining six beams feature horizontal openings at the flange's bottom. The ultimate capacity of RC beams with a Hz opening T-section is reduced by 16.5%. The ultimate capacity of RC beams with a Vt opening T-section is reduced by 27%. In comparison, the ultimate capacity of RC beams with a Hz opening rectangular section is reduced by 25.7%. The ultimate capacity of RC beams with a Vt opening rectangular section is reduced by 52%.

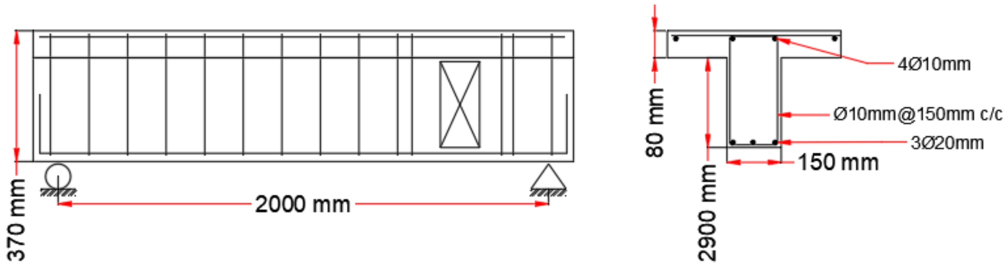

Figure 6. Beam span and cross-section with reinforcement [26]

2.1.2. Deflection

The existence of openings in RC beams may cause a decrease in deflection with less amount of applied load [24, 25, 27]. The deflection values of beams with different shapes of openings may vary; for example, with an opening area of 125 mm x 125 mm, the square shape reduces the deflection by 59%, while the circular shape reduces it by 46%. Conversely, a rectangular opening with a 72% area of a square opening results in a 36% reduction in the deflection of the RC beam [24].

Morsy and Barima [25] tested 24 beams with different opening shapes, orientations, and locations. The observed results are in Table 4:

Table 4. Percentages of decreasing due to openings

Beam with opening	% of decrease due to opening
Square 120mm x 120 mm	22.7%
Rectangular 98 mm x 147 mm Hz	18.18%
Rectangular 170 mm x 85 mm Vt	16.3%
Rectangular 85 mm x 170 mm Hz	20.9%
Rhombus 120mm x 120 mm	18.18%
Circular D= 135mm	9.09%

The beam deflection is slightly affected when the opening is resized from a small square to a bigger rectangle shape. Abdalla, et al. [27] tested ten RC beams, where two of them had openings of 100 mm x 100 mm, two of them had openings of 200 mm x 100 mm, another two had openings of 300 mm x 100 mm, and the final three beams had openings of 300 mm x 150 mm. The control specimen had no openings. Figure 7 shows beam dimensions and their reinforcement. Changing the opening from a small square shape to a greater rectangular opening, particularly before cracking, slightly affects the beam deflection. By comparing the outcomes, it is evident that the opening height is the primary factor influencing the load-deflection behavior of beam openings.

2.1.3. Crack Initiation Load

Rectangular openings develop crackers faster than circular openings, and they develop larger cracks [26, 28, 29]. Hassan, et al. [26] reported that the initial hair crack in a solid beam begins in the flexural zone. Secondly, an inclined crack appears close to support and spreads toward the maximum moment region. As the loads increased, additional flexural and shear cracks emerged, ultimately leading to the failure of the beams in shear. The first crack in the beam with a horizontal opening appeared in the bottom corner of the opening near the support. As the stresses at the bottom chord increased, numerous inclined cracks formed, leading to the beam's shearing failure at the opening side. The first hair crack in the beam, which had a vertical opening, appeared at the bottom corner of the opening close to the support. This crack was smaller than the previous one and spread towards the point load. Eventually, the opening side collapsed in shear.

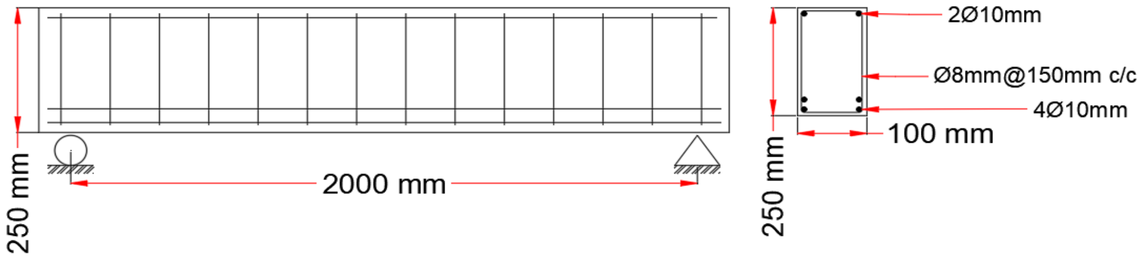

Figure 7. Beam span and cross-section with reinforcement [27]

Circular shape has less load crack initiation than other shapes. Hamid, et al. [28] studied several RC beams, including two with round openings and one control solid beam. Every beam has the following measurements: 1900 mm long, 300 mm deep, and 150 mm wide, as shown in Figure 8. The beam's shear span is 450 mm, and there are 500 mm between the two loading points. Therefore, this study considers a short shear span, *a/d < 2.5 (a/d* means shear span to effective depth ratio).

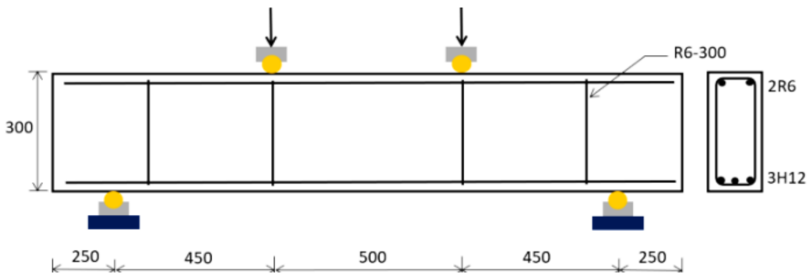

Figure 8. Beam span and cross-section with reinforcement [28]

On the other hand, the opening affects first cracking load reduction; for instance, Agag, et al. [29] had 13 RC beams with a cross-section of 160 mm by 400 mm and a total length of 2400 mm (2200 mm effective length). Two high-tensile steel bars with 12 mm and 10 mm diameters, respectively, served as the primary and secondary steel reinforcements. The stirrups were composed of mild steel bars, each with a diameter of 8 mm and a spacing of 200 mm. Figure 9 provides detailed information about the dimensions of the beam and its reinforcements. Generally, the openings are square, 200 mm x 200 mm. Four of them are in mid-span, four of them are in an under-load position, and the last four of them are in the shear zone.

The beam with an opening in the shear zone reduced the first crack load by approximately 40.9% compared to the control beam.

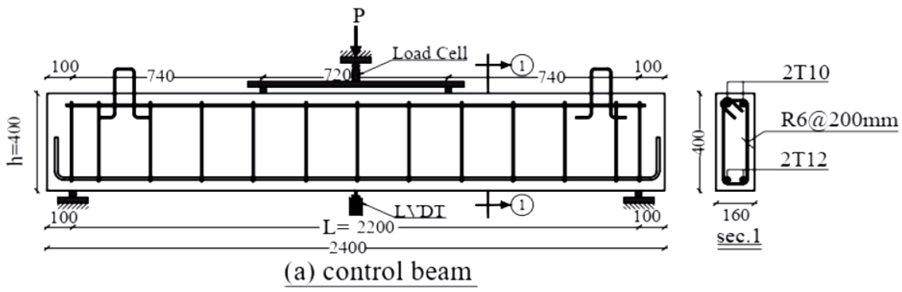

Figure 9. Beam span and cross-section with reinforcement [29]

The results are tabulated in Table 5.

Table 5. Opening shape, cracking load, and failure position

Reference	Beam dimensions L mm	b mm	h mm	Opening shape Circular	Square	Rectangular	Crack initiation load %	Failure Position
Hassan, et al. [26]	2000	150	370			200x100 mm^2 HZ	71%	Shear
Hassan, et al. [26]	2000	150	370			100x200 mm^2 Vt	57%	Shear
Hamid, et al. [28]	1900	150	300	1φ100 mm			50%	Shear
Hamid, et al. [28]	1900	150	300	2φ100 mm			39%	Shear
Agag, et al. [29]	2400	160	400		200x200 mm^2 @midspan		100%	Flexure
Agag, et al. [29]	2400	160	400		200x200 mm^2 under load		79%	Shear
Agag, et al. [29]	2400	160	400		200x200 mm^2 @shear zone		59%	Shear

The rectangular shape of RC beams experienced a horizontal delay in crack initiation, whereas the circular shape of the opening, despite its small area, experienced the first crack much later.

2.2. Locations of Openings

2.2.1. Load Carrying Capacity

The beam's capacity will decrease when RC beam openings are closer to supports [24, 29, 30]. For instance, Al-Sheikh [24] reported an average reduction of 13% in the ultimate load-carrying capacity when the opening is situated in the shear zone, while this average reduction is only 5% when the openings are in the flexure zone. Therefore, it is advised to have the openings in the flexural zone when it is urgent to do so because, in general, making an opening in the beam significantly reduces its load capacity, particularly when the opening is in the shear zone [24].

The beam, which had openings in the shear zone, underload position, and midspan, experienced a reduction in the maximum load of the control beam by approximately 47%, 36%, and 4%, respectively [29].

Anwer and Taha [30] tested 7 RC beams to support the theory further. Two of the beams, serving as control specimens, had a shear span ratio of 3.61 and 1.5, respectively. Five beams featured openings: one with an 80 mm diameter in the shear region, two with 40 mm and 80 mm diameters in the flexure region, and the same in the shear-flexure region. Every specimen had the same dimensions, as shown in Figure 10. There were bigger holes, D/h > 0.4 (D/h means hole diameter to specimen height ratio), in the beam in the shear, shear with flexure, and flexure zones. These holes made the ultimate load 13% lower on average. Tiny openings in the flexure and shear with flexure zones reduced the beam's ultimate load by 4.8% and 19.8%, respectively.

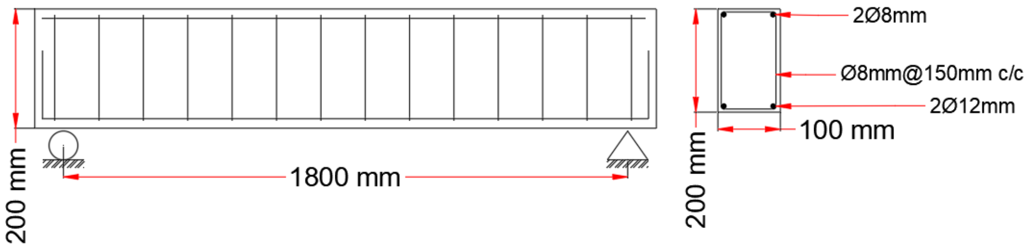

Figure 10. Beam span and cross-section with reinforcement [30]

Table 6 shows the effect of opening location on the reduction of load-carrying capacity of RC beams.

Table 6. Opening position and load-carrying capacity

Reference	Beam dimensions			Opening position			Load carrying capacity %
	L mm	b mm	h mm	Shear	Flexure	On support	
Al-Sheikh [24]	1800	120	250	φ140 mm			44%
Al-Sheikh [24]					φ140 mm		92%
Al-Sheikh [24]						φ140 mm	62%
Morsy and Barima [25]	1500	120	300	120x120 mm^2			64%
Morsy and Barima [25]	1500	120	300		120x120 mm^2		77%
Agag, et al. [29]	2200	160	400	200x200 mm^2			53%
Agag, et al. [29]	2200	160	400		200x200 mm^2		96%
Agag, et al. [29]	2200	160	400			200x200 mm^2 (under load)	64%
Anwer and Taha [30]	1800	100	200	φ80mm			81%
Anwer and Taha [30]	1800	100	200		φ80mm		94%
Anwer and Taha [30]	1800	100	200			φ80mm	55%

2.2.2. Deflection

The existence of openings in RC beams and the deflection of their beams, especially if openings exist at the mid-span of beams, increases with the same applied load [30, 31]. Anwer and Taha [30] tested beams with circular openings at the shear, flexure, and support zone, each with a diameter of 80 mm. The results of their deflection were 58%, 69%, and 46%, respectively, when compared to the control beam's deflection. The opening in the shear zone had a greater impact than the opening in the flexure zone.

El Ame, et al. [31] studied ten beams with dimensions of the supported beam 200 mm in depth, 150 mm in width, and 2000 mm in span. The strength of the concrete was 30 MPa. Figure 11 shows the beam detail.

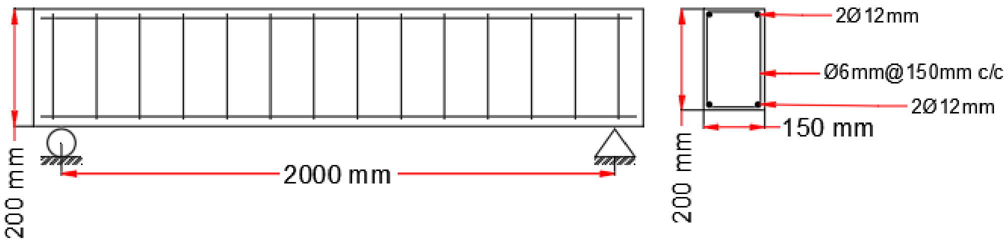

Figure 11. Beam span and cross-section with reinforcement [31]

The horizontal placement is 300 mm from the supports, and three locations are suggested: 0.5, 0.55, and 0.6 times the beam's effective depth. The investigation focused on how the reduction in the concrete area within the section's various chords will affect the serviceability and strength of beams. The suggested opening diameters were 0.3, 0.4, and 0.5 times the effective depth d. A decreased flexural capacity results from openings above the mid-depth because they lessened the area required for the rectangular compressive stress block to form. As a result, there was a deflection and less curvature in the beam. The deflection results show that the center of the circular opening sits at 0.5d, 0.55d, and 0.6d from the bottom of the RC beam, signifying 73%, 76%, and 81%, respectively, with d denoting the effective depth of the RC beam.

2.2.3. Crack Initiation Load

Due to the location of the openings, cracks appeared rapidly in the opening zone next to the shear zones [25, 30]. Morsy and Barima [25] tested 12 beams with openings in different locations, and their results of the first cracking load are as follows:

For openings in the shear locations, square and rectangular horizontally with an aspect ratio of 1.5, and rhombus equals 100%. However, rectangular horizontally and vertically with an aspect ratio equal to 2, the first cracking load did not occur (which means it suddenly reached the ultimate load without the first crack appearing). On the other hand, the beam with the circular opening, its first cracking load, was increased by 105%. The first cracking disappeared completely for all opening shapes in the flexure zone. This indicates that the failure occurred swiftly, without any cracks to indicate its imminent collapse.

The initial cracking load of RC beams decreased more when an opening occurred in the flexure zone than in the shear zone. Anwer and Taha [30] reported that circular openings with a diameter of 80 mm were found at shear, flexure, and support locations. The reductions of first cracking loads were 25%, 33%, and 16% in shear, flexure, and on the support zone of the RC beam, respectively.

2.3. Sizes of Openings

2.3.1. Load Carrying Capacity

It has been proven that enlarging the openings' size negatively affects the beams' strength [18, 27, 31, 32]. Abdalla, et al. [27] tested beams with different opening sizes, comparing the ultimate load-carrying capacity of different samples with that of the control beam without an opening. The load-carrying capacity of a square opening measuring 100 mm by 100 mm, a rectangular opening measuring 200 mm by 100 mm, a rectangular opening measuring 300 mm by 100 mm, and a rectangular opening measuring 300 mm by 150 mm, respectively, was 49%, 52%, 49%, and 27% respectively. Conversely, a rectangular opening with a 150 mm height and the same width has a load-carrying capacity of 55% compared to an opening with the same width and a 100 mm height.

Increasing the opening size of RC beams causes them to reduce their load-carrying capacity. El Ame, et al. [31] tested beams with vertical openings of varying sizes and locations. The openings were circular and had 50 mm, 65 mm, and 80 mm diameters. The location varied vertically, with the center of the opening situated 80 mm, 88 mm, and 96 mm away from the top fiber of the beam cross-section. The results are in Table 7.

Table 7. Opening size and load-carrying capacity

Beam dimensions			Center of opening at 80 mm		Center of opening at 88 mm		Center of opening at 96 mm	
L mm	b mm	h mm	Opening diameter mm	% of ultimate load	Opening diameter mm	% of ultimate load	Opening diameter mm	% of ultimate load
2000	150	200	φ50	58	50	61	50	64
2000	150	200	φ65	55	65	60	65	63
2000	150	200	φ80	53	80	52	80	57

Increasing the opening size reduces the ultimate load of the section by reducing the area resistance in the RC beam's cross-section. On the other hand, the location of the opening also influences its strength; when the opening is close to the upper fiber, the RC beam's strength decreases due to the smaller compression chord. Özkılıç, et al. [32] investigated twelve small-scale beam specimens. Each specimen measured 1000 mm in length and 100 mm to 150 mm in cross-section. Every specimen had a longitudinal tension reinforcement of 2φ10 and a compression reinforcement of 2φ6, as shown in Figures 12-a and 12-b. The stirrups were 100 mm (bending specimens) and 160 mm apart (shear specimens). Two transverse openings, one in each half span, were present in every specimen. Five distinct openings with diameters 30 mm, 40 mm, 50 mm, 60 mm, and 70 mm were used. The corresponding opening D/h are 0.2, 0.27, 0.33, 0.4, and 0.47 for these diameters.

The load-carrying capacity loss for bending specimens varied from 11% for a beam with a 30 mm diameter opening to 30% for a beam with a 70 mm diameter opening. For shear specimens, however, the outcomes were different. The reduction for shear specimens ranged from 8% for small openings to 50% for larger openings.

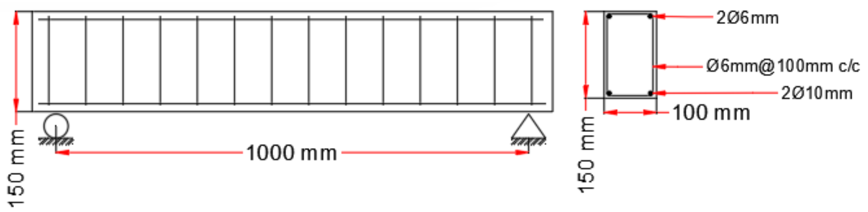

Figure 12-a. Beam dimensions and reinforcement / bending specimen [32]

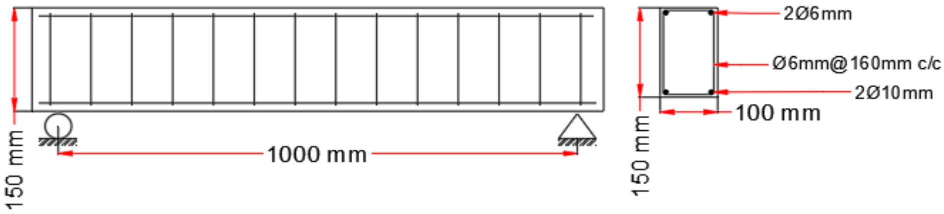

Figure 12-b. Beam dimensions and reinforcement / Shear specimen [32]

Mondal, et al. [18] cast ten beams, each measuring 2000 mm, had a height of 260 mm and a width of 150 mm. Nine of these beams are divided into three groups, each containing three beams, while one remains solid. The first set of three beams had an opening 100 mm wide by 100 mm, the second group had an opening 200 mm by 100 mm, and the third group had an opening 300 mm by 100 mm, as shown in Figure 13. The load-carrying capacity of RC beams was slightly affected by widening the rectangular opening from 200 mm to 300 mm. The results showed that as the opening size increased, the ultimate load of RC beams decreased. An RC beam with a 100 mm x 100 mm opening had an ultimate load of 67%. When the opening size increased to 200 mm x 100 mm, the ultimate load decreased to 62%. When the opening size reaches 300 mm x 100 mm, the ultimate load drops to 61%. This indicates that the horizontal increase in opening size has less impact than the vertical increase. It is advantageous for the researcher to experiment with various opening shapes and locations to obtain different results.

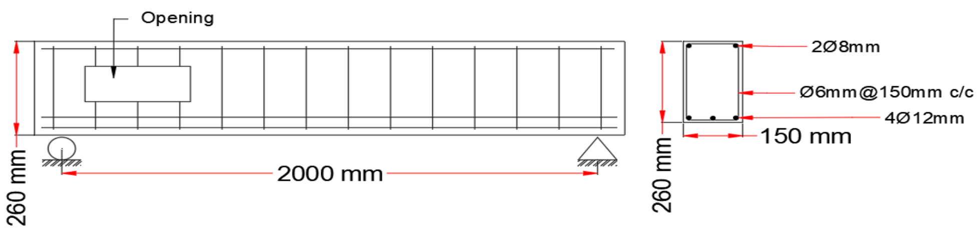

Figure 13. Beam section and reinforcement [18]

2.3.2. Deflection

The amount of deflection in RC beams increases due to the increase in opening size for any opening shapes [18, 33-35]. Mondal, et al. [18] observed that solid beams undergo less deformation than beams with openings. Beams with openings of 100 mm x 100 mm, 200 mm x 100 mm, and 300 mm x 100 mm exhibit greater deflections. The RC beams with openings of 100 mm x 100 mm, 200 mm x 100 mm, and 300 mm x 100 mm deflected 106%, 117%, and 170%, respectively, compared to the control beam.

Chin, et al. [33] conducted tests on specimens with a cross-section of 120 mm x 300 mm and measured 2000 mm in length. The beam's effective span measured 1800 mm, and the effective depth of the reinforcement was 280 mm. The tension reinforcement used was 12 mm. The rectangular opening measured 800 mm in length by 140 mm in height (total area = 112,000 mm²) and was rectangular and rounded with φ140 mm (total area = 107,786 mm²). Given the a/d ratio of 0.50, placing a plywood box in the middle of each beam, as depicted in Figure 14, created a massive opening. From the test, it was observed that the large openings in the mid-span of beams, both rectangular and rounded, lost almost 50% of their capacity because they extended past the loading points. The chord members bend similarly to Vierendeel, with points of contra flexure located in the middle of each chord. This was because the solid beam segments to the left and right of the opening put axial tension and compression on the chord members. The results vary between the two openings due to differences in their sizes and shapes. The rectangular opening had 33% of total control beam deflection but 36% for a rectangularly rounded opening.

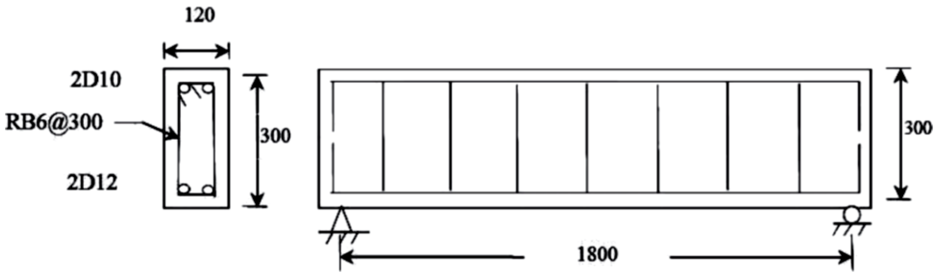

Figure 14. Beam dimensions and reinforcement [33]

For focusing, Elansary, et al. [34] tested a beam measuring 150 mm x 300 mm, and its respective total and clear spans were 2200 mm and 2000 mm, respectively. As illustrated in Figure 15, three longitudinal bars were positioned with a diameter of 16 mm and two longitudinal bars with a diameter of 10 mm at the bottom and top of each beam, respectively, to provide comparable longitudinal and transversal reinforcement. Closed stirrups measuring 8 mm in diameter and 200 mm apart are positioned along the opening length of the beams, with one extra stirrup at each side of the opening. Seven beams were tested: the control beam had no opening, two had an opening measuring 100 mm x 200 mm, two had an opening measuring 150 mm x 200 mm, and the remaining two had an opening measuring 100 mm x 300 mm. Complete openings at the beam's supports. The load-deflection behavior of beams with tiny opening sizes was comparable to that of the solid beam reference. Because the opening had no effect on the beams' overall load-deflection behavior, layer-by-layer analysis effectively forecasted the load-deflection behavior of both the reference beam and those with openings.

The research would benefit from testing different opening shapes and sizes and concrete resistances. When comparing the behavior of beams with openings to that of reference beams, the impact of the opening size is evident. The beam with an opening of 300 mm x 100 mm was broader than the beam with an opening of 200 mm x 100 mm, but it had the same opening depth. The reference beam, the beam with an opening of 200 mm x 100 mm, and the beam with an opening of 300 mm x 100 mm all had similar load-deflection relationships, with no more than 5% differences. This shows that the opening depth had a bigger effect on the load-deflection behavior than the opening breadth. The reference beam and the beam with an opening of 200 mm x 100 mm exhibit 50% greater deflections than the beam with an opening of 200 mm x 150 mm following cracking.

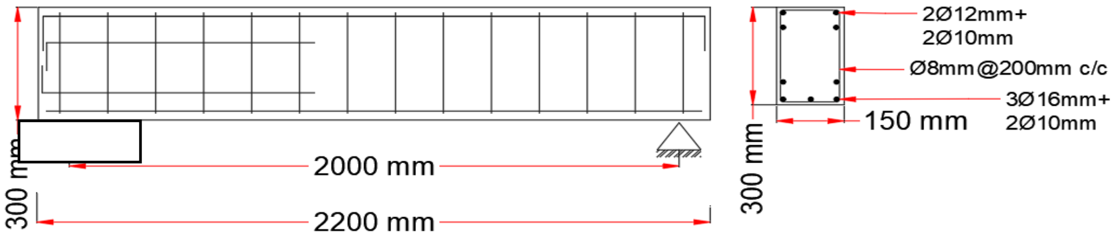

Figure 15. Beam dimensions and reinforcement [34]

According to Abdel-Kareem, et al. [35], the samples consisted of twelve RC beams, each measuring 120 mm x 300 mm and 2600 mm long. Two applied stresses separated by 800 mm and the supports by 2400 mm. Two 16-mm and two 12-mm reinforcements were placed at the bottom, and two 10-mm reinforcements at the top. There were 8mm stirrups available, spaced 200mm apart, as illustrated in Figure 16. Each opening intercepted one or more of the stirrups, cut during the construction of the reinforcing cage, to replicate the conditions of adding an opening to an existing beam. The entrance has two shapes: a square 150 mm x 150 mm and a rectangle 100 mm x 300 mm. The results indicate that the beam with a 150 mm x 150 mm opening deflected 64% of the control beam without an opening, while another beam with a 300 mm x 100 mm deflected 56% of the control beam. The larger size of the final opening, which reduces the cross-section area of the RC beam and places more stress on concentration than the initial one, accounts for this discrepancy.

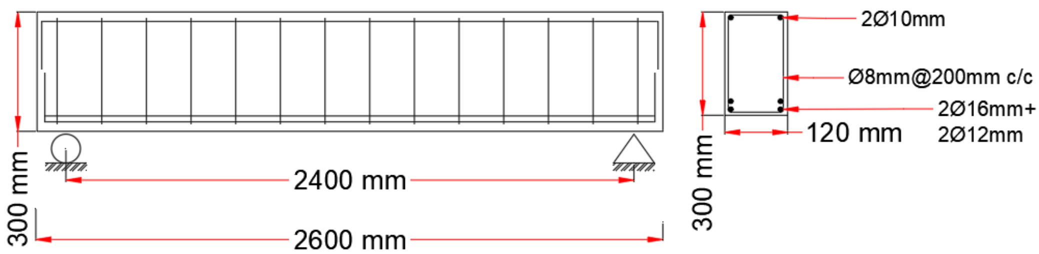

Figure 16. Beam dimensions and reinforcement [35]

2.3.3. Crack Initiation Load

Usually, increasing opening sizes causes a decrease in crack initiation load for RC beams [27, 33]. According to Abdalla, et al. [27], the first load cracking of beams features openings of various sizes of 100 mm x 100 mm, 200 mm x 100 mm, 300 mm x 100 mm, and 300 mm x 150 mm, which were 83%, 43%, 67%, and 17%, respectively. Increasing the opening size logically reduces the first load-cracking. However, the second beam (with an opening of 200 mm x 100 mm) showed less first load cracking than the third one (with an opening of 300 mm x 100 mm), possibly due to personal error factors during the test. The last beam experienced a significant decrease in its load due to increased opening height.

The difference in opening size was an effect on the first load cracking in RC beams; according to Chin, et al. [33], the first load crack of an RC beam with an opening rectangular rounded total area of 107786 mm² is 42% of the first load cracking for the control beam without any opening, but in the case of an existing rectangular opening with a total area of 112000 mm², the first load cracking is 40%. This decrease in the initial load cracking is attributed to the larger size of the opening.

3. Conclusions

Openings in reinforced concrete (RC) beams generally reduce their load-carrying capacity, especially in the shear span, which has a greater impact than the flexure span. The center of the beam is the best location for openings, as it minimally affects the flexure zone. Circular openings cause the least reduction in ultimate load, while large openings near the shear zone can cause significant reductions in load and excessive shear cracks. In beams with openings less than 25% of the beam depth in the shear zone, the reduction in load is minimal, around 2.5%. Large openings can reduce the ultimate load by up to 64% and decrease deflection by up to 57%. The presence of transverse openings in beams with less shear reinforcement leads to greater reductions in shear capacity. Circular openings perform the best, followed by horizontal rectangular openings. Significant strength reductions occur when openings cover 30-40% of the beam depth, and such designs should be avoided unless properly reinforced. Finally, RC beams with openings in the pure flexure zone can support their maximum load if the top chord depth is adequate.

Declaration of Competing Interest: The authors declare they have no known competing interests.

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