

Review

Review of the Structural Performance of Beams and Beam–Column Joints with Openings

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Abstract: The need for openings in RC structures has increased, but their presence significantly affects the performance and strength of the structures. While small openings can be managed with additional reinforcement, dealing with large openings in reinforced or pre-stressed concrete members is challenging due to the lack of technical information and specific guidelines. This research provides an up-to-date overview of RC beam–column joints that incorporate web openings and evaluates appropriate strengthening methods. The research discusses the classification of openings in RC beams, considering factors such as size and shape. Additionally, it examines the failure modes of RC beams in relation to flexural and shear behavior when web openings are present. The research also provides a comprehensive review of various strengthening techniques, outlining their advantages and disadvantages. In conclusion, larger openings in beams result in reduced strength, while increasing loads lead to higher deflection, strain, and cracking until failure. Openings are classified as small or large based on their impact on beam behavior. Multiple smaller openings are preferred over a single large opening when size becomes excessive. Optimal placement is in the middle of the section to ensure adequate concrete coverage for the chords. Sufficient concrete and depth are essential for ultimate compression during bending and effective shear reinforcement.

Keywords: frame joints; reinforced concrete; opening; cyclic performance; strengthening



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1. Introduction

The practice of using reinforced concrete beams with openings to accommodate utility pipes is a common construction method, as it facilitates the efficient routing of pipes through the structure. However, these openings can have a significant impact on the behavior of the structure, which makes it crucial to examine their effects on the behavior of the beam–column joints under cyclic loading. The presence of openings can reduce the effective cross-sectional area of the beam, leading to a decrease in its strength and stiffness. Moreover, openings can produce stress concentrations, which can cause the member to crack and potentially fail. Cyclic loading can significantly affect joint behavior causing damage to the structure.

Studies have been conducted on reinforced concrete beams with openings to understand the effects of opening size, shape, and mechanisms of crack initiation and propagation. For example, research on beams with different opening sizes showed that the presence of openings reduces the capacity of shear load and can lead to brittle failure. Most cracks occurred around the shear zone opening, in the direction of the compression zone. Other cracks appeared at the moment zone and increased in length as the load increased until the beam failed [1].

Another study found that the presence of an opening led to an increase in deflection of around 50% and a decrease in load capacity of approximately 50%. Circular openings were also investigated in previous research [2,3]. One study examined the impact of a small circular opening on the shear and flexural behavior, as well as the ultimate capacity, of beams made of normal and high-strength concrete [4,5]. The results indicated that increasing the diameter of the opening reduced the ultimate strength of the beam, while deflection, strain, and cracks increased with the load until failure. In the following sections of this literature review, the most significant outlines of previous studies carried out by researchers which are about the behavior of beams with openings are reported.

2. RC Beam Web Opening Classification

This section explores the categorization of reinforced concrete (RC) beams that have web openings, focusing on the size and placement of these openings. Openings in these beams can be sorted into two categories: small and large. The optimal location for an opening depends on its size. In practice, web openings come in a variety of shapes, such as circular, rectangular, diamond, triangular, trapezoidal, and irregular. Circular and rectangular shapes are most commonly employed.

Mansur and Tan mentioned in their research that the classification of an opening as small or large should be based on the structural response of the beam [6–8]. An opening is considered small if it allows the beam to continue behaving like a conventional beam. Conversely, if the beam's typical behavior is disrupted due to an opening, that opening is categorized as large [9].

The discussion further includes the Vierendeel action concept and the development of a four-hinge mechanism as a precursor to failure. These hinges are presumed to develop in the truss chord members, specifically at a distance equal to half the overall depth of a chord member ($h/2$), measured from the vertical faces of the opening. This is illustrated in Figure 1, with the subscripts t and b denoting the top and bottom chords, respectively.

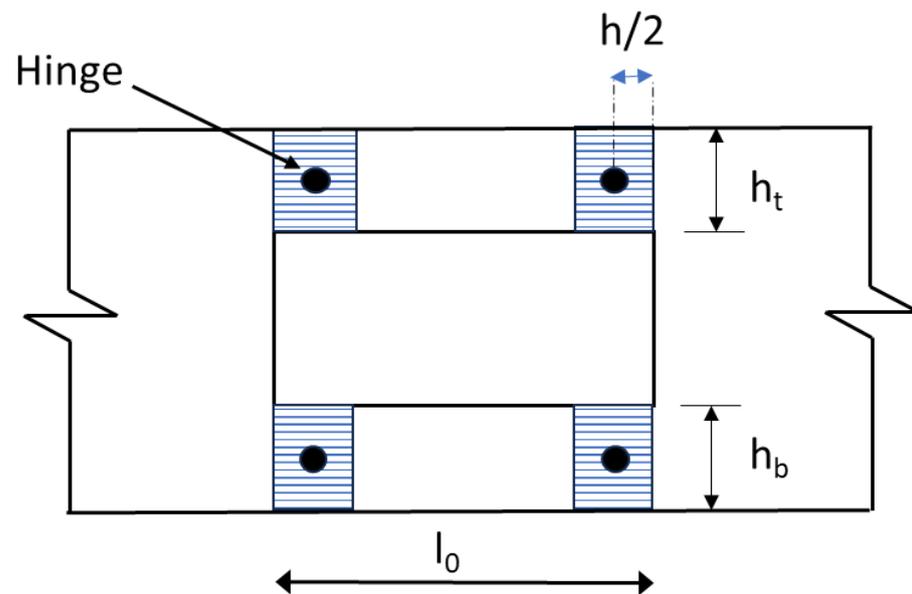


Figure 1. Forming of hinge in RC beam with opening.

The definition of small and large openings depends on the length of the opening in relation to the larger of the two depths, h_t and h_b . When the length of the opening is less than or equal to h_{max} , it is considered a small opening, while an opening longer than h_{max} is considered a large opening. It is important to ensure that the members above and below the opening have adequate depth to accommodate the reinforcement scheme, and in the case of circular openings, an equivalent square should be used to determine h_{max} [6].

A. Ahmed et al. [10] referenced Mansur and Tan's recommendations on the size and location of web openings in beams. For T-beams, they suggest that openings be level with the flange to facilitate construction. Rectangular beams usually should have openings at their mid-depth. The proximity of openings to supports or concentrated loads is also crucial; they should be situated no closer than half the beam's depth to avoid shear failure. As for the depth of the openings, it should not exceed 50% of the beam's total depth. Finally, considerations regarding the chord members' stability—particularly the compression chord—and deflection limits influence the opening's length. If a larger opening is required, it is advisable to choose multiple smaller openings that serve the same purpose rather than a single large one.

In the case of beams with rectangular openings, the typical Vierendeel action is often linked to the formation of a four-hinge plastic mechanism. However, B. Aykac et al. [11] observed a crucial deviation in beams with circular openings, where this Vierendeel action was notably absent. The lack of such a mechanism in beams with circular openings significantly underscores the impact that the shape of the opening has on the structural behavior and failure patterns of the beams.

3. Effect of Opening Location and Size on Behavior of the Beam

The positioning of web openings in concrete beams may have a significant impact on the overall structural behavior of beams, impacting aspects such as the load-carrying capacity, the amount of deflection, and the stress distribution [12,13]. Incorrect positioning or size of these openings may lead to a reduction in the beam's overall efficiency. In order to maintain the necessary level of structural performance, it is thus vital for engineers to take into consideration the effects of web opening location which is shown in previous studies that greatly affect the behavior of beam-column joints [14,15].

Mohamed et al. conducted a study focusing on the analysis of reinforced concrete deep beams with web openings, using the damaged plasticity model in ABAQUS software version 6.7 [16]. Their investigation included a variety of beam configurations: simply supported deep beams subjected to both three-point and four-point bending, as well as continuous deep beams. These configurations were tested both with and without web openings. The study revealed that web openings intersecting anticipated compression struts could lead to a significant reduction, of 35%, in the beam's load-bearing capacity and should thus be avoided. In contrast, web openings that did not intersect with these struts resulted in a more modest 6–8% reduction in capacity, dependent on the dimensions of the openings. The depth of the opening is the most critical factor for maintaining overall beam capacity, with the study recommending a maximum opening depth of 20% of the beam's overall depth to prevent a reduction in capacity exceeding 10%. Additionally, the study found that reinforcement distribution could also impact the beam's capacity. A reinforcement range between 0.1 and 0.2 times the overall depth (H) of simply supported deep beams was recommended to minimize capacity reductions between 0.3% and 12%.

Ahmed M. Sayed conducted a separate study using finite element (FE) modeling as a tool to predict the shear load capacity of reinforced concrete beams with vertical openings [17]. This research employed parametric analyses to evaluate how the location, number, and dimensions of the openings could affect the ultimate shear load capacity and failure modes of the beams. The FE model's predictions were validated by comparing them to existing experimental data on similarly structured beams. The study concluded that the FE model was accurate in predicting both the failure modes and the ultimate load capacities. A key finding was that increasing the diameter of circular openings resulted in a reduction in both the maximum deflection at the failure load and the ultimate load capacity. The diameter of the opening was found to have a more noticeable effect than the number of openings in these parameters. Furthermore, the study demonstrated that the vertical opening diameter, when placed on the width of the beam section, had a more significant effect than the shear span length on the maximum deflection at failure load and ultimate load capacity.

In their study, D. N. Jabbar et al. [18] focused on understanding the shear behavior of reinforced concrete beams, conducting experiments on four beams subjected to three-point loading. The research comprehensively captured all material properties, leading to a detailed analysis of the ultimate loading capacity and deflection at the beams' mid-span. An in-depth examination of the control failure mode was also presented. The study's findings highlighted that beams with circular openings demonstrated superior performance. These beams, compared to those with different opening shapes, exhibited higher ultimate loading capacities and lower deflections, indicating their effectiveness in structural applications. The research also revealed that all the tested beams showed bi-linear load–deflection curves, a characteristic suggesting considerable ductility. This observation points to the necessity for further research, particularly in understanding how additional variables, like the reinforcement of openings with steel rebars and the eccentricity of openings, might influence the shear behavior of perforated RC beams.

In their study, A. El-Kareim et al. [19] explored the shear behavior of flanged deep beams with web openings, comparing them to traditional beams with a rectangular section. They found that beams with openings failed along two sets of diagonal cracks near the openings, in contrast to the diagonal failure of solid beams. The presence of openings not only reduced stiffness but also led to earlier crack formation. Flanges in the beams provided early warning signs of failure and enhanced shear distress. While strength degradation in rectangular beams was abrupt, it was more gradual in flanged beams. Additionally, flanged beams showed a higher reserve capacity than their rectangular counterparts, indicating their enhanced structural resilience.

W. Mansour's [20] study, employing finite element modeling, explored the impact of web openings on the structural performance of continuous reinforced concrete (RC) beams, particularly when these beams were reinforced with fiber-reinforced polymer (FRP) layers. The research specifically examined the location of openings. In the study, continuous beams were classified into three zones based on internal straining actions. Zone I is characterized by upward shear forces and experiences less than the maximum sagging moment. Zone II faces both upward and downward shear forces, along with the maximum sagging moment. Zone III is subject to downward shear forces coupled with the maximum hogging moment, categorized into three zones, I, II, and III, and their size, ranging from 22,500 to 75,000 mm², affected the beams' ultimate load capacity and failure patterns. The study's findings indicated a significant decrease in load capacity due to web openings. Beams with openings in zone II experienced the most substantial reduction, with load capacities decreasing by 7.3% to 66.1% compared to control beams. However, the study noted an improvement in load capacities when opening locations were altered. In beams with openings in zone I, the reduction in load capacities ranged from 5.3% to 26.3%, while in zone III, the reduction was between 13.6% and 52.7%. Notably, zone I was identified as the most optimal location for minimizing structural impact. Additionally, the study emphasized that the opening area was a critical factor influencing both the load capacity and stiffness of the beams. For instance, the specimen with the largest opening (75,000 mm²) showed a 26.3% reduction in load capacity compared to the solid beam, B-0-0. As the opening area decreased, there was a noticeable improvement in both load capacity and stiffness.

3.1. Configuration of Longitudinal and Shear Reinforcement and Design Method

From Figure 2,

V_t = shear force at the top chord;

V_b = shear force at the bottom chord;

M_t = moment at the top chord;

M_b = moment at the bottom chord;

N_t = normal force at the top chord;

N_b = normal force at the bottom chord.

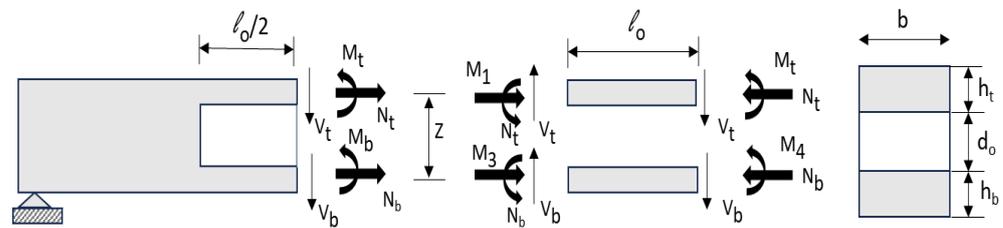


Figure 2. Detail of large opening section [6].

$$M_m = M_t + M_b, \quad (1)$$

where M_m is the moment at the center of the opening.

$$V_m = V_t + V_b \quad (2)$$

where V_m is the shear force at the center of the opening.

$$V_t = (M_2 + M_1)/L_o = 2M_2/L_o; V_b = (M_4 + M_3)/L_o = 2M_4/L_o \quad (3)$$

$$V_t = V_m \left[\frac{I_t}{I_t + I_b} \right] \quad (4)$$

$$M_1 = -\frac{Wl_o^2}{8} - \frac{V_t l_o}{2} \quad (5)$$

$$M_2 = -\frac{Wl_o^2}{8} + \frac{V_t l_o}{2} \quad (6)$$

$$M_3 = -\frac{V_b l_o}{2} \quad (7)$$

$$M_4 = \frac{V_b l_o}{2} \quad (8)$$

Ensuring the continuity of longitudinal reinforcement both at the bottom and the top of the section, especially adjacent to the web opening, is crucial. Engineers commonly use idealized column interaction diagrams along with the strain compatibility method to design the extra reinforcement needed for each chord member to withstand the combination of bending moment and axial force. A thorough evaluation of all the possible combinations of bending moments and axial forces within the relevant interaction diagram is necessary to confirm that the reinforcement is sufficient. This is especially true for the flexural capacity of the top chord, making it essential to design the reinforcement accordingly.

When it comes to shear forces, they can typically be calculated using Equation (3). While the design condition depends on known forces—usually comparable to those found in standard reinforced concrete beams and slabs—it is important to note that the ACI-318 [9] guidelines specify that the effects of axial forces in the chord members need to be integrated into the design process. This ensures that all structural considerations are adequately accounted for, leading to a more robust and reliable structure.

3.2. Deflection Design

While conventional methods for ensuring serviceability often involve limiting the effective span-to-depth ratio to control deflection, this approach is not entirely accurate when dealing with beams that have openings. Given this limitation, it becomes imperative to calculate the actual service load deflection for a more precise assessment. In such scenarios, analyzing the beam under its ultimate load becomes a useful strategy, particularly when the reinforcement detailing is clearly specified. This allows for a more accurate

evaluation of the beam's serviceability under real-world conditions, ensuring that it meets the necessary deflection requirements.

4. Strengthening of RC Beam with Web Opening Using FRP

This section will present research carried out in the past on enhancing the performance of RC beams with web opening by using FRP strengthening methods. Reinforcement is necessary around openings in concrete beams to maintain their strength and stiffness. However, it is impossible to achieve this reinforcement when openings are made after construction or through drilling. To counteract the loss of strength in beams with openings, researchers have employed various techniques, including the application of fiber-reinforced polymer (FRP) strengthening. This approach focuses on improving the confinement, flexural, and shear strength of the region surrounding the beam's opening. The following paragraphs of this section present a selection of studies that have successfully employed FRP strengthening to reinforce beams with openings.

Research in the area of structural engineering has delved into the potential of fiber-reinforced polymers (FRPs) for strengthening various structural elements [4,20–31]. One innovative approach, studied by X. F. Nie et al. [25], was termed flexural weakening–shear strengthening. This involved creating a web opening in the beam to reduce its flexural capacity and then enhancing its shear strength through external FRP reinforcement. Known as the WOLSS technique, this method was tested on eight full-scale reinforced concrete beams. The proposed system involved wrapping the web chord fully with carbon fiber-reinforced polymer (CFRP) and adding two CFRP U-jackets to the beam's web, properly anchored. The method significantly increased shear capacity and improved ductility during failure. In a related study, Karzad et al. [32] evaluated the externally bonded carbon fiber polymer (EB-CFRP) repair technique for improving the shear strength of deficient beams. Tests were carried out on two types of repaired specimens: those lacking stirrups and those with minimal steel stirrups. Through the combined use of EB-CFRP and epoxy injection, the repaired beams exhibited a nearly 95% increase in shear strength compared to their original capacities. Yet another experiment [33] focused on the efficacy of various reinforcement techniques for beams with openings. Internal reinforcements, such as diagonal bars and additional steel bars, were used around the openings before casting, while externally bonded CFRP sheets were applied post casting. The study concluded that the choice of strengthening technique varied depending on the location of the opening. Numerical analyses also supported the real-world experiments. These finite element method (FEM) studies investigated a range of strengthening techniques and opening locations in reinforced concrete beams [34]. The numerical results were found to align well with experimental findings, confirming that the applied strengthening approaches successfully enhanced various structural attributes like strength capacity, deflection, and failure modes. In a study conducted by W. Mansour in continuous RC beams with web openings in area where the beam is subject to downward shear forces coupled with the maximum hogging moment, applying FRP layers above and below the opening effectively restored their reduced load capacity. However, this method did not result in the steel reinforcement reaching yield stress; thus, no ductility index was observed. In contrast, this approach did enhance both stiffness and mid-span deflection at the ultimate load compared to beams without such strengthening. For beams with openings in the same area of the beam, when FRP layers were applied over the entire height of the beam, they recorded the highest ultimate loads among all specimens studied. This full-height strengthening technique also significantly increased the ductility of the beams.

Wan et al. [35] conducted a study to examine the impact of bond imperfections, such as existing cracks and poor workmanship, on the behavior of FRP-strengthened concrete members. The simulation involved inducing cracks on the concrete surface, which had a dual effect on bond behavior. For cracks with a width of 3 mm, both bond strength and fracture energy decreased due to the resulting material damage. However, for cracks with

a width of 1 mm, the bond performance was improved due to stress redistribution caused by the presence of cracks.

El-sisi et al. [36] conducted a study on the effect of a drilled opening on the performance of reinforced concrete beams. To simplify the process, square holes were cut into the shear and tension zones of the reinforced concrete samples. The authors found that the presence of a tension-zone opening did not have a significant impact on the beam's strength, with the maximum reduction in failure load being only 14% for the $360 \times 120 \text{ mm}^2$ opening in comparison to the undrilled control beam. Despite the small improvement in strength compared to the control beam, the strengthening beams exhibited a significant increase in strength ranging from 31% to 46%, indicating the effectiveness of the FRP strengthening method.

5. Beam–Column Joints with Opening under Cyclic Loading

For openings located near supports, failure occurs in the same way as in a solid beam, with the failure line always passing through the center of the opening. This is because the opening creates stress concentration, leading to the formation of diagonal tension cracks. As these cracks propagate, the beam eventually fails when the remaining concrete and reinforcement can no longer carry the applied load. To mitigate the negative effects of openings on beam–column joints, adequate reinforcement detailing around the openings is crucial, including the use of horizontal and vertical reinforcement bars to provide sufficient confinement and improve the structural integrity of the beam–column connection and the effect of unreinforced beam web openings on the behavior of concrete beam–column joints [37].

Experimental studies on RC beam–column joints with openings on the beam web have demonstrated the effectiveness of various reinforcement strategies in improving their cyclic performance. For example, researchers have found that the provision of supplementary transverse reinforcement around the openings can enhance the confinement of the concrete, thereby increasing the joint's load-carrying capacity and energy dissipation under cyclic loading [38]. Moreover, extending longitudinal reinforcement through the openings and providing adequate anchorage can ensure better force transfer and maintain the structural integrity of the joint.

Amin et al. [21] developed a numerical model to predict the performance of beam–column connections (BCCs) with nearby web openings under cyclic loading. The model was validated using experimental results and other numerical models. The parametric study investigated the effects of reinforcements around the opening, reinforcement stirrups, opening proximity to support, and opening aspect ratio. Key findings include the significant impact of reinforcement around the opening in enhancing the failure load, particularly for wide rectangular openings near supports. Reinforcement in the connection core has a lesser impact on enhancing failure load compared to reinforcement around the opening and is more efficient with square openings near supports. Opening proximity to support significantly reduces the failure load compared to control BCC without openings, especially for wide rectangular openings without reinforcement. Additionally, failure load decreases by 37.78% and 27.04% for wide rectangular and square openings without reinforcement, respectively. With reinforcement, the decreases are 24.16% and 15.21%, respectively.

6. Conclusions

1. The presence of openings in beams notably alters their structural behavior and failure patterns. While solid beams tend to fail along a single diagonal crack, beams with openings exhibit failure through multiple diagonal cracks around the opening areas. This change in failure mode is a critical factor in assessing the structural integrity and safety of beams with openings.
2. Beams with circular openings generally demonstrate a higher load-bearing capacity and lower deflection compared to those with other shapes of openings. This finding

- suggests that the shape of the opening is a significant factor in determining the overall performance of the beam.
3. The stability of the chord parts, notably the compression chord, combined with deflection serviceability requirements, dictates the size of an opening. It is better to have multiple smaller openings rather than one large opening if the opening gets too big.
 4. Openings are ideally located in the middle of the section and sized to ensure enough concrete coverage for the chords above and below. The aim is to have sufficient concrete for ultimate compression during bending and enough depth for efficient shear reinforcement.
 5. To avoid a region vulnerable to shear failure, openings should not be nearer than half the beam depth (D) to the supports.
 6. The length of the openings is limited by the stability of the chord elements, the compression chord, and serviceability deflection requirements.
 7. The opening's depth is vital, with a suggested cap of 20% of the total beam depth ($0.2d$) to prevent over 10% capacity reduction. The spread of reinforcements affects the beam's strength, recommending a span of $0.1\text{--}0.2h$ for basic supported beams, limiting capacity losses to between 0.3% and 12%.
 8. An increase in the diameter of circular openings led to decreased load capacity at failure. The diameter of the opening has a more noticeable effect than the number of openings.
 9. Ensuring that longitudinal reinforcement continues through openings with proper anchorage guarantees better force distribution and preserves the joint's structural integrity.
 10. The presence of flanges in concrete beam and additional reinforcement, particularly around the openings, can enhance the structural performance of the beam. Flanges provide early warning signs of failure and contribute to improved load distribution, while additional reinforcement can mitigate the adverse effects of openings on the beam's strength and stiffness.
 11. The use of FRP strengthening methods has been shown to be effective in enhancing the performance of reinforced concrete beams with web openings. This technique is particularly beneficial in scenarios where traditional reinforcement methods are not feasible, such as when openings are created post construction or through drilling.
 12. To mitigate the negative effects of openings on beam–column joints and enhance cyclic performance, adequate reinforcement detailing around the openings is essential. This includes the use of horizontal and vertical reinforcement bars to provide sufficient confinement and improve the structural integrity of the beam–column connection.

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References

1. Shoeib, A.E.-K.; Sedawy, A.E.-S. Shear strength reduction due to introduced opening in loaded RC beams. *J. Build. Eng.* **2017**, *13*, 28–40. [CrossRef]
2. Kumar, N. Behavior of Reinforced Concrete Beam with Opening. 2017. Available online: https://iaeme.com/MasterAdmin/Journal_uploads/IJCIET/VOLUME_8_ISSUE_7/IJCIET_08_07_062.pdf (accessed on 21 September 2023).
3. Hua, L.J.; Tang, H.S.; Leong, W.K.; Sia, H.T. Behaviour of Reinforced Concrete Beams with Circular Transverse Openings under Static Loads. *J. Sci. Appl. Eng.* **2020**, *3*, 1–16.

4. Amiri, J.V.; Hosseinalibygie, M. Effect of small circular opening on the shear and flexural behavior and ultimate strength of reinforced concrete beams using normal and high strength concrete. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004.
5. Ali, S.R.M.; Saeed, J.A. Shear capacity and behavior of high-strength concrete beams with openings. *Eng. Struct.* **2022**, *264*, 114431. [[CrossRef](#)]
6. Mansur, M.A.; Kiang-Hwee, T.; Chen, W.F. *Concrete Beams with Openings: Analysis and Design (New Directions in Civil Engineering)*, 1st ed.; CRC Press: Boca Raton, FL, USA, 1999.
7. Mansur, M.A. Effect of openings on the behaviour and strength of R/C beams in shear. *Cem. Concr. Compos.* **1998**, *20*, 477–486. [[CrossRef](#)]
8. Fu, L.; Wang, H.; Nakamura, H.; Wang, D. Mechanism of shear strengthening for RC beam by drilling web openings based on experiment and 3D RBSM analysis. *Eng. Fail. Anal.* **2023**, *145*, 107048. [[CrossRef](#)]
9. Sobhy, A.; Aboul Nour, L.; Hassan, H.; Elsisy, A. Behavior of Structural Concrete Frames with Hybrid Reinforcement under Cyclic Loading. *Frat. Ed. Integrità Strutt.* **2021**, *15*, 70–81. [[CrossRef](#)]
10. Ahmed, A.; Fayyadh, M.M.; Naganathan, S.; Nasharuddin, K. Reinforced concrete beams with web openings: A state of the art review. *Mater. Des.* **2012**, *40*, 90–102. [[CrossRef](#)]
11. Aykac, B.; Kalkan, I.; Aykac, S.; Egriboz, Y.E. Flexural behavior of RC beams with regular square or circular web openings. *Eng. Struct.* **2013**, *56*, 2165–2174. [[CrossRef](#)]
12. Hafiz, R.B.; Ahmed, S.; Barua, S.; Chowdhury, S.R. Effects of Opening on the Behavior of Reinforced Concrete Beam. Available online: www.iosrjournals.org (accessed on 21 September 2023).
13. Jasim, W.A.; Allawi, A.A.; Oukaili, N.K.A. Effect of Size and Location of Square Web Openings on the Entire Behavior of Reinforced Concrete Deep Beams. *Civ. Eng. J.* **2019**, *5*, 209–226. [[CrossRef](#)]
14. Saleh, M.; AlHamaydeh, M.; Zakaria, M. Finite element analysis of reinforced concrete deep beams with square web openings using damage plasticity model. *Eng. Struct.* **2023**, *278*, 115496. [[CrossRef](#)]
15. Özkılıç, Y.O.; Aksoylu, C.; Yazman, Ş.; Gemi, L.; Arslan, M.H. Behavior of CFRP-strengthened RC beams with circular web openings in shear zones: Numerical study. *Structures* **2022**, *41*, 1369–1389. [[CrossRef](#)]
16. Mohamed, A.R.; Shoukry, M.S.; Saeed, J.M. Prediction of the behavior of reinforced concrete deep beams with web openings using the finite element method. *Alex. Eng. J.* **2014**, *53*, 329–339. [[CrossRef](#)]
17. Sayed, A.M. Numerical study using FE simulation on rectangular RC beams with vertical circular web openings in the shear zones. *Eng. Struct.* **2019**, *198*, 109471. [[CrossRef](#)]
18. Jabbar, D.N.; Al-Rifaie, A.; Hussein, A.M.; Shubbar, A.A.; Nasr, M.S.; Al-Khafaji, Z.S. Shear behaviour of reinforced concrete beams with small web openings. *Mater. Today Proc.* **2021**, *42*, 2713–2716. [[CrossRef](#)]
19. El-Kareim, A.; Arafa, A.; Hassanin, A.; Atef, M.; Saber, A. Behavior and strength of reinforced concrete flanged deep beams with web openings. *Structures* **2020**, *27*, 506–524. [[CrossRef](#)]
20. Mansour, W. Numerical analysis of the shear behavior of FRP-strengthened continuous RC beams having web openings. *Eng. Struct.* **2020**, *227*, 111451. [[CrossRef](#)]
21. Amin, S.; Elwan, S.; Elzeiny, S.; Hamad, M.; Deifalla, A. Numerical modeling the effect of an opening on the behavior of exterior beam-column connections under cyclic loading. *J. Build. Eng.* **2021**, *40*, 102742. [[CrossRef](#)]
22. Teng, J.G.; Lam, L.; Chen, J.F. Shear strengthening of RC beams with FRP composites. *Prog. Struct. Eng. Mater.* **2004**, *6*, 173–184. [[CrossRef](#)]
23. Danraka, M.N.; Mahmud, H.M.; Oluwatosin, O.J.; Student, P. Strengthening of Reinforced Concrete Beams Using FRP Technique: A Review of the Conceptual Design of Composite Sections View Project Nothing View Project Oluwatosin Job Ojo-kupoluyi Nigeria Sugar Institutie Strengthening of Reinforced Concrete Beams Using FRP Technique: A Review. 2017. Available online: <http://ijesc.org/> (accessed on 21 September 2023).
24. Vijayalakshmi, N.; Kalaivani, M.; Murugesan, A.; Thirugnanam, G.S. Experimental Investigation of RC-Beam Column Joint Strengthening by FPP Wrapping. *Int. J. Civ. Struct. Eng.* **2010**, *1*, 35–49.
25. Nie, X.; Zhang, S.; Teng, J.; Chen, G. Experimental study on RC T-section beams with an FRP-strengthened web opening. *Compos. Struct.* **2018**, *185*, 273–285. [[CrossRef](#)]
26. A.P.S. Analysis of Beam Openings Strengthened by Carbon Fibre Reinforced Polymer (CFRP) Using ANSYS. 2013. Available online: www.ijsr.net (accessed on 21 September 2023).
27. Salih, R.; Zhou, F.; Abbas, N.; Mastoi, A.K. Experimental investigation of reinforced concrete beam with openings strengthened using frp sheets under cyclic load. *Materials* **2020**, *13*, 3127. [[CrossRef](#)] [[PubMed](#)]
28. Nie, X.; Zhang, S.; Teng, J. Strengths of RC beams with a fibre-reinforced polymer (FRP)-strengthened web opening. *Compos. Struct.* **2021**, *258*, 113380. [[CrossRef](#)]
29. Nie, X.; Zhang, S.; Chen, G.; Yu, T. Strengthening of RC beams with rectangular web openings using externally bonded FRP: Numerical simulation. *Compos. Struct.* **2020**, *248*, 112552. [[CrossRef](#)]
30. Elsanadedy, H.M.; Al-Salloum, Y.A.; Almusallam, T.H.; Alshenawy, A.O.; Abbas, H. Experimental and numerical study on FRP-upgraded RC beams with large rectangular web openings in shear zones. *Constr. Build. Mater.* **2018**, *194*, 322–343. [[CrossRef](#)]
31. Mwonga, M.M.; Kabubo, C.; Gathimba, N. Effect of polyethylene terephthalate fibres on the structural performance of reinforced concrete beams with openings in the shear region. *Constr. Build. Mater.* **2023**, *369*, 130539. [[CrossRef](#)]

32. Karzad, A.S.; Al Toubat, S.; Maalej, M.; Estephane, P. Repair of reinforced concrete beams using carbon fiber reinforced polymer. *MATEC Web Conf.* **2017**, *120*, 01008. [[CrossRef](#)]
33. Agag, F.; Ahmad, S.S.E.; Sallam, H.E.-D.M. Experimental assessment of different strengthening techniques for opening in reinforced concrete beams. *Frat. Ed. Integrità Strutt.* **2022**, *16*, 549–565. [[CrossRef](#)]
34. Pimanmas, A. Strengthening R/C beams with opening by externally installed FRP rods: Behavior and analysis. *Compos. Struct.* **2010**, *92*, 1957–1976. [[CrossRef](#)]
35. Wan, B.; Jiang, C.; Wu, Y.-F. Effect of defects in externally bonded FRP reinforced concrete. *Constr. Build. Mater.* **2018**, *172*, 63–76. [[CrossRef](#)]
36. El-Sisi, A.A.; El-Emam, H.M.; El-Kholy, A.E.-M.I.; Ahmad, S.S.; Sallam, H.M.; Salim, H.A. Structural Behavior of RC Beams Containing Unreinforced Drilled Openings with and without CFRP Strengthening. *Polymers* **2022**, *14*, 2034. [[CrossRef](#)]
37. Mansur, M.A. Ultimate strength design of beams with large openings. *Int. J. Struct.* **1988**, *8*, 107–125.
38. Liu, T.-J.; Chen, S.-W.; Feng, Z.-H.; Liu, H.-Y. Effect of Web Openings on Flexural Behaviour of Underground Metro Station RC Beams under Static and Cyclic Loading. *Adv. Civ. Eng.* **2020**, *2020*, 1210485. [[CrossRef](#)]

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