https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

A State-of-the-Art-Review on Reinforced Concrete Beams with Web Openings

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ABSTRACT
In recent decades, the need for introducing openings in RC beams has been increasing. Several utility services, such as electrical cables, water pipes, air conditioning, and network connections, require one or more openings for easy bypassing. Web openings significantly affect the service and ultimate stages of RC beams. In the service stage, more excessive deformation is induced by opening presence due to stiffness reduction. Furthermore, high stresses in the ultimate stage result from web openings, especially in the opening region. Openings disturb the stress flow due to the abrupt change in the geometry leading to a stress concentration around the opening. Several researchers have studied different methods in order to compensate for the loss in beam deflection and strength. This paper presents a state-of-the-art review of RC beams with web opening and discusses some proper strengthening techniques. The classifications of openings in RC beams in terms of size, shape, execution time, and direction are discussed. Moreover, RC beams' flexural and shear failure modes due to openings are presented. Several strengthening techniques are discussed in this review study to distinguish their pros and cons. It can be concluded that beams with openings at the flexure span behave better than the shear span. Also, circular openings are preferable among all shapes. Moreover, strengthening RC beams with openings using ferrocement and SHCC significantly enhances the beams' performance. Last, this paper also sheds more light on the importance of considering the opening in the preliminary design stages to avoid unexpected and undesirable failures.

Keywords: *RC beams; opening; strength; deflection; strengthening*.

1. Introduction

An opening inside the reinforced concrete (RC) beam became crucial in several buildings, especially in service floors. Architectural and mechanical engineers usually suffer from the floor's clear height limitation. Hence, it became necessary for structural engineers to consider openings when designing RC beams to pass ducts and pipes through them. In fact, different applications inside the building need this kind of opening in the structural beams [1]. For example, plumbing, telephone cables, air-conditioning outlets, internet connections, electricity wires, and sewage pipelines pass through those ducts and pipes inside RC beams [2–4]. Figure 1 depicts an existing example of RC beams with a web opening inside one of the buildings. The main problem of having an opening in RC beams is the abrupt change in the geometry, which significantly affects the structural behavior of the element [5–9]. Numerous studies have been carried out in order to develop different techniques to strengthen the region around the opening in conventional concrete beams [10–13]. It is worth mentioning that the opening's location and size significantly affect its impact on the beam's response. Consequently, studying RC beams with an opening has been an area of interest worldwide.

Figure 1: Example of openings passing through RC beams in an existing building [14]

2. Objectives

This review paper aims to summarize and cover the use of opening in RC beams and the development factors through the following points:

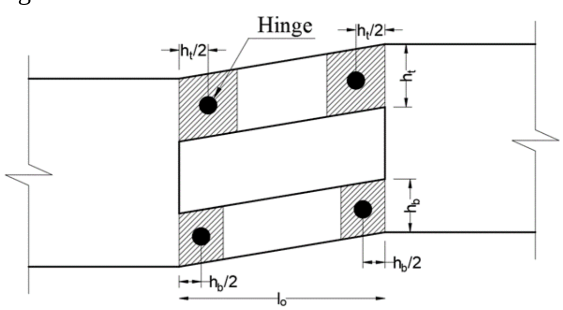
- Summarize the classification of openings in RC beams
- Understand the behavior of RC beams with web openings
- Discuss various failure modes of RC beams with openings
- Illustrate the effect of different strengthening techniques on RC beams' behavior with openings
- Present some recent experimental and numerical studies of RC beams with openings

3. Classification of Openings in RC Beams

This section discusses the classification of openings in RC beams in terms of size, location, shape, and execution time.

3.1 Opening Size

In general, several research studies divided the opening in terms of its size into small and large [15]. However, others have mentioned another in-between size, namely medium [16]. Somes et al. considered openings with a depth exceeding 0.25 the total web depth as large [17]. On the other hand, Mansur recommended considering the opening as large if its clear length exceeds the maximum thickness of the top and bottom chord members [18], as shown in Figure 2.



Small opening: $l_o \leq h_{max}$

Large opening: $l_o > h_{max}$

Where, h_{max} is the larger of h_t and h_b

Figure 2: Classification of opening in terms of size [18]

This classification was based on the formation of plastic hinges at beam failure at the four corners of the opening, as mentioned by Mansur. It is worth mentioning that the clear classification of the opening as large or small should be based on the overall beam behavior. In other words, if the beam with a web opening follows the traditional beam theories, the opening can be classified as small as its effect is negligible. In contrast, when the beam behaves in an untraditional way and does not follow the usual theory of the beam, the opening should be classified as large and much care has to be taken to understand the new behavior of the beam [19]. Nevertheless, structural design engineers usually adopt one of the aforementioned classification techniques, away from investigating the actual beam behavior, to easily distinguish between small and large openings.

3.2 Opening Shape

Another classification of openings in RC beams is based on their shapes. Openings could have different shapes according to their applications. For example, Amiri et al. [20] showed different opening shapes, such as circular and rectangular openings, which are the most common shapes in practice. Other several shapes, such as diamond, trapezoidal, triangular, and irregular, have been presented in different studies, as described in Figure 3 [21]. Different design approaches and recommendations have been developed to accommodate the presence of the opening in RC beams [22–27].

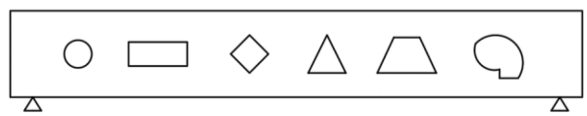


Figure 3: Classification of opening in terms of shape [21]

3.3 Opening Execution Time (before/after concrete casting)

It is worth mentioning that the opening can sometimes be fabricated after concrete casting. For example, changing the function of the building requires some new pipe connections, which might require making some openings in the existing structural elements. In such cases, strengthening of the beam using the proper technique has to be implemented. On the other hand, the pre-planned opening inside the beam has to be taken into consideration in the preliminary design stages, as mentioned in [28].

3.2 Opening Direction

Openings in RC beams could be placed in several locations. For example, Abdul-Razzaq et al. studied the effect of vertical openings in the beam's flange in terms of ultimate loads and corresponding deflections [13], as shown in Figure 4. In contrast, the effect of horizontal openings was reported in a study by Abdulrahman et al. [29]. Figure 5 describes the tested beam with a horizontal opening at mid-span. Based on the findings of each study, it can be concluded that the vertical opening has a more significant effect on the overall beam response than horizontal openings. This could be attributed to the more considerable concrete loss in the compression side in the case of the vertical opening. On the other hand, the beam behavior with an opening near the support (shear zone) differs entirely from the opening near the mid-span of the beam (flexure zone). Ali et al. studied the effect of changing opening location [30]. They found that placing the opening away from the supports leads to better beam performance. The same results were reported by Elsayed et al. [31].

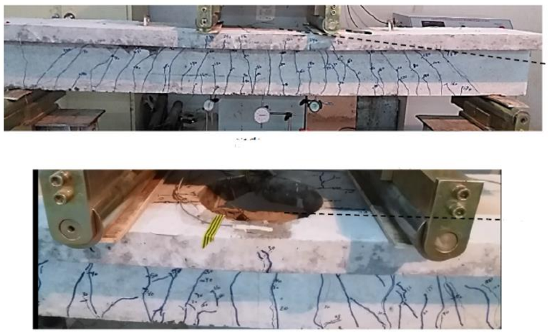


Figure 4: Crack patterns of a beam with a vertical circular opening [13]

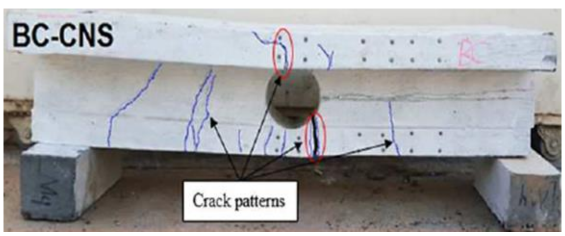


Figure 5: Crack patterns of a beam with a horizontal circular opening [29]

4. Guidelines for the Selection of Openings' Location and Size

Mansur and Tan reported some valuable recommendations for the optimum size and position of the opening in RC beams [32]. For example, they recommended not to increase the opening depth beyond 50% of the total beam depth (D) to avoid excessive reduction of the beam's capacity. Additionally, the opening should be placed at least 0.5D away from support, concentrated load, or adjacent openings. The main reason for that is to avoid the critical zone where the reinforcement is most likely congested and the shear failure is dominant. Also, they recommended dividing the single long opening into multiple openings with the same total area. This can help achieve the required serviceability limits and ensure the stability of the top and bottom chord members. Furthermore, they mentioned that the best location for the opening in T-beams is precisely below the flange, which facilitates the construction process. On the other hand, the typical opening location for rectangular beams is at the section's mid-depth. However, it is highly recommended to slightly adjust the opening along the beam depth to ensure enough concrete cover for the reinforcement in the lower chord member; meanwhile, having a sufficient concrete part in compression to avoid brittle concrete failure of the upper chord member.

5. Failure Modes

This section discussed different failure modes for beams with openings [33, 34]. Small openings in the flexure zone have insignificant effects on the beams' strength and failure mode. Figure 6 (a) depicts a schematic drawing of a beam with a small opening, which failed in a traditional ductile manner. In contrast, large openings in the flexure zone reduce the concrete part in the compression side, decreasing the beam's ultimate capacity. The failure mode of beams with a large opening size in the flexure zone is generally controlled by concrete crushing of the upper chord members, as shown in Figure 6 (b). On the other hand, different scenarios are observed for beams with an opening in the shear span. Figure 7 shows two different failure modes for beams with a small opening. Such beams usually fail due to tension diagonal, as shown in Figure 7 [32]. The failure crack may pass through the center of the opening, which is called beam-type failure. In contrast, it may be separated into two paralleled cracks at two opposite sides of the opening and called frame-type failure. On the other hand, large openings generally fail in shear by forming a mechanism of four plastic hinges at corners, as shown in Figure 8 [32]. Several research studies focused on understanding the behavior of RC beams under different conditions [35, 36].

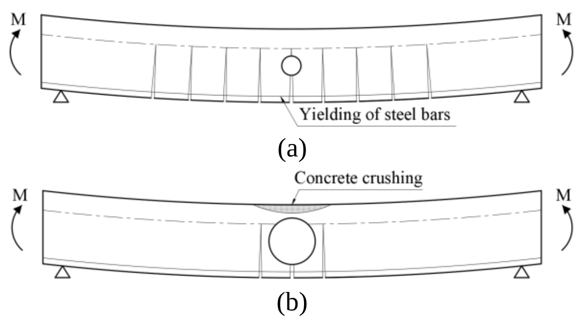
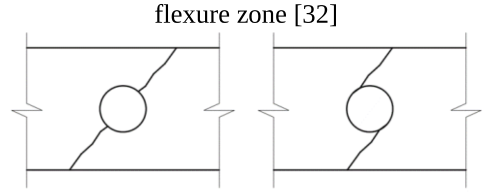


Figure 6: Schematic drawing showing failure modes of a beam with (a) small and (b) large openings in the flexure zone [32]



(a) Beam-type failure (b) frame-type failure

Figure 7: Shear failure modes of beams with a small opening [32]

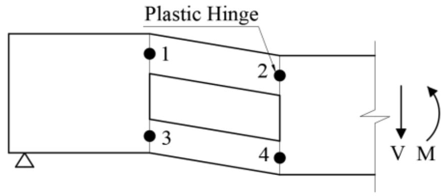


Figure 8: Collapse mechanism of beams with a large opening in the shear zone [32]

6. Recent Studies on Beams with Openings

This section presents some recent research studies regarding RC beams with web opening. Moreover, different strengthening techniques to compensate for the loss in strength of the beam are discussed.

6.1 Beams with Unstrengthened Openings

Daniel argued in his study that buildings with floors rested on beams in two orthogonal directions increase over time. Meanwhile, mechanical engineers require openings inside the beam to pass their facilities. Therefore, Daniel experimentally investigated five RC beams' behavior with elongated openings [37]. Figure 9 demonstrates a schematic drawing showing the four-point loading test. The main test parameter was the length of the opening, as depicted in Table 1. The author concluded that by increasing the opening length, both shear and flexural modulus were reduced. Vierendeel action mechanism was observed for beams with large openings. Specifically, four plastic hinges were formed at the opening corners, leading to the beam's failure. In comparison, other beams with smaller opening lengths showed a failure due to diagonal shear cracks.

Table 1: Details of test specimens [37]

Specimen	h (mm)	Opening area %	Opening size	
			a (mm)	b (mm)
B0	667	0	-	-
B1		5	110	50
B2		10	220	
B3		15	330	
B4		20	440	

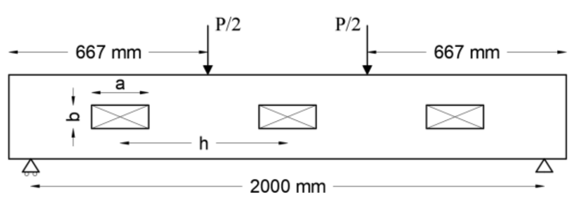


Figure 9: schematic drawing showing the test setup [37]

Figure 10 shows the load-deflection response for the test specimens. It can be noticed that the longer the opening, the higher the deflection values recorded at ultimate. Moreover, Daniel mentioned that the increase in the opening length resulted in a significant decrease in the test specimen's strength and a reduction in the beam's stiffness. Additionally, a nonlinear FE analysis was carried out and validated with the experimental results at the end of the study. The numerical results considerably matched the experimental findings, as mentioned by Daniel [37].

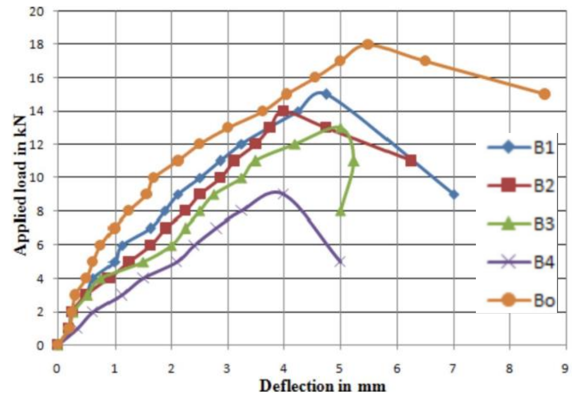


Figure 10: Load-deflection response for test specimens [37]

6.2 Beams with Openings Strengthened with FRP

A study by Nie et al. tested experimentally six large-scale T-section beams with different sizes of web opening [38]. The way of making the opening inside the beam was varied in order to investigate the effectiveness of each beam opening technique. Figure 11 demonstrates the details of the test specimens. The authors preferred investigating the test beams while the flange was in tension (i.e., inverted T-section) as they considered that the T-beam in negative bending is much more significant than that in positive bending. The results exhibited that making an opening in existing beams is feasible as long as an appropriate strengthening technique is used to compensate for the loss in strength and ductility. In Nie et al.'s study [38], the authors used the FRP sheets for strengthening, and this method showed good performance and ease of installation. In addition, Figure 12 shows the failure modes of all test specimens after testing. The unstrengthened beams showed a severe cracking pattern along with a significant drop in the load-deflection behavior. In contrast, other strengthened beams with FRP sheets exhibited enhanced crack distribution. In particular, the authors mentioned that the strengthening technique using CFRP jackets with spike anchors was not only able to restore the strength of the beam but also enhance the ductility of the tested beam. Moreover, the authors proposed a model that can predict the flexural capacity of such beams with small and medium opening sizes. The analytical results showed an excellent agreement with the experimental data results.

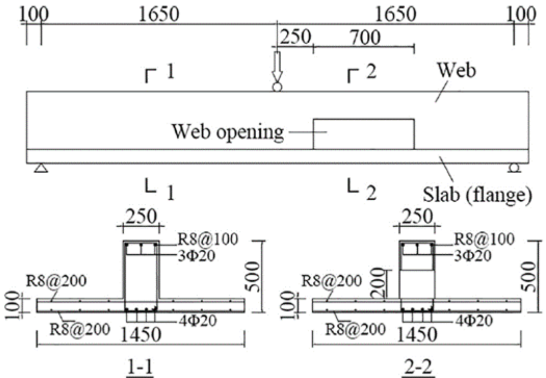


Figure 11: Details of test specimens [38]

Figure 12: Failure modes of test specimens [38]

Salih et al. investigated the behavior of RC beams experimentally with web opening at the shear zone and flexural zone under cyclic loading [39]. Figure 13 shows the geometry and the reinforcement details of test specimens in addition to the location of the openings. The authors used CFRP sheets as an external strengthening technique, as shown in Table 2. Two wrapping shapes were reported as a test parameter; the first one was vertically placed, while the second one was inclined. The experimental results included test specimens' hysteretic load-deflection response, failure modes, energy dissipation, stiffness degradation, and ductility. The authors found that the adopted strengthening technique could enhance the overall beam performance. Specifically, the ultimate capacity of the strengthened beam with an opening in the shear zone increased by approximately 63% compared to the control one. In comparison, the strengthened beam with an opening at the flexure zone showed an increase in strength by 73% rather than the control beam. Figure 14 demonstrates the stiffness degradation for all test specimens. The test beams with an opening at either the shear zone or flexure zone strengthened with inclined CFRP sheets exhibited better stiffness behavior than beams with vertical sheets.

Table 2: Details of test specimens [39]

ID	Opening size (mm)	FRP schemes	FRP organization
B0	-	-	-
BR-1	140X90	-	-
BR-2		Vertical	2 layers (0/90)
BR-3		Inclined	2 layers (60/120)
BR-4		Vertical	2 layers (0/90)
BR-5		Inclined	2 layers (60/120)

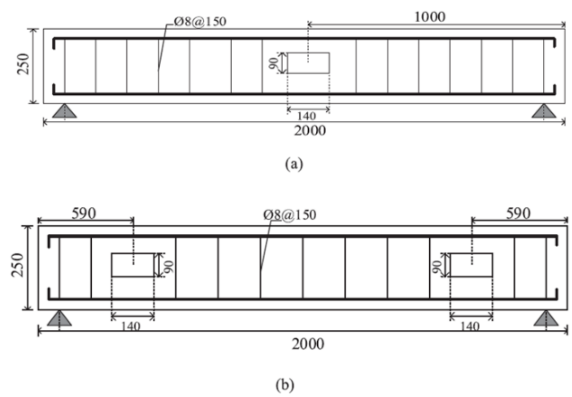
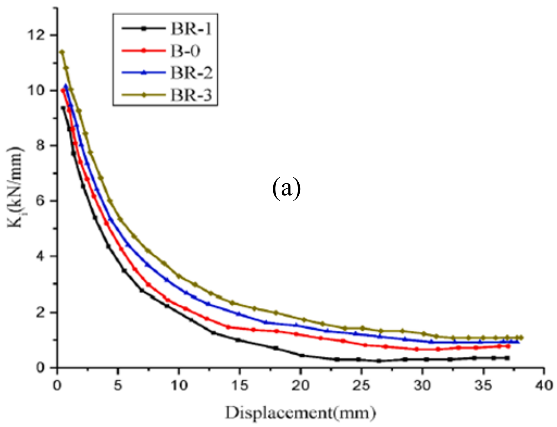


Figure 13: Details of test specimen [39]

The authors also proposed a numerical approach to predict the experimental results [39]. Constitutive and concrete damage plasticity models were used to simulate the concrete's nonlinear mechanical properties. The numerical results showed good convergence with the experimental results. Accordingly, the numerical models were used in studying other parameters. In particular, the length of the FRP sheets, the opening size, and location were investigated numerically. It should be noted that the maximum recorded error in the deflection was approximately 8% between numerical and experimental results. In comparison, it was around 10% for the load-carrying capacity. Finally, the authors recommended using a double-layer of CFRP sheets for strengthening beams with a large opening. This recommendation is considered the mosteffective method in terms of the beam's safety with the specific test conditions.



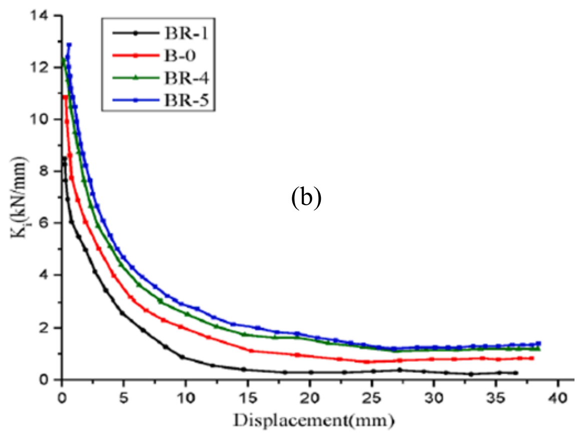


Figure 14: stiffness degradation for beams with opening in (a) shear zone and (b) flexure zone [39]

A recent study conducted by Elansary et al. in 2022 investigated the shear behavior of reinforced concrete beams with a web opening at the shear zone experimentally [40]. The four-point loading test was used, in the abovementioned study, on six beams with different opening sizes. Figure 15 depicts the reinforcement details and beams' dimensions. Table 3 describes the test parameters in addition to the implemented strengthening techniques. The authors reported the load-deflection behavior, cracking pattern, failure modes, and strain values for all test specimens. Figure 16 shows the cracking pattern and failure modes for all six beams. The experimental results revealed that the beam with a large opening exhibited a significant reduction of around 35% compared to the control beam. In contrast, by strengthening the opening with CFRP sheets, an average rise of 25% was observed compared to counterparts of unstrengthened beams. In particular, specimen B6 experienced a diagonal shear crack at failure near the support away from the opening, which emphasizes the strengthening effect [40].

Table 3: Details of openings and strengthening for beam specimens [40]

ID	Opening size (mm)	Distance from support	Strengthening
B0	-	-	No
B1	200 x 100	0	No
B2	200 x 150	0	No
B3	300 x 100	0	No
B4	200 x 100	150 mm	No
B5	200 x 150	0	Yes
B6	300 x 100	0	Yes

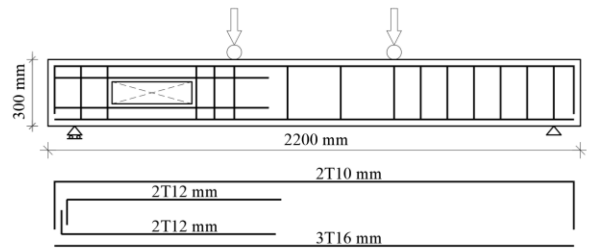


Figure 15: Specimen fabrication and geometry details [40]

Figure 16: Crack patterns and failure modes [40]

6.3 Beams with Openings Strengthened with Steel Plates

Robert et al. studied the effect of steel plates as a strengthening technique for beams with openings [41]. They experimentally tested seven beams with dimensions of 150 mm, 300 mm, and 2000 mm in width, depth, and length, respectively, as shown in Figure 17. All beams were reinforced longitudinally with 3T12 mm and 2T10 mm in tension and compression sides, respectively. Stirrups with a diameter of 8 mm were placed every 150 mm to resist shear stresses. The four-point loading test setup was adopted in their study. The test parameters included an opening in the flexure zone, an opening in the shear zone, and two openings in the shear zone. Table 4 demonstrates the details of the test parameters. The load-deflection behavior for all test specimens is shown in Figure 18.

Table 4: Details of beam specimens [41]

ID	Specimen details
CB	Control
BCOF	Flexure opening
BCOS1	Shear opening
BCOS2	Two shear openings
BCFSP	Flexure opening - strengthened
BCSSP1	Shear opening - strengthened
BCSSP2	Two shear openings - strengthened

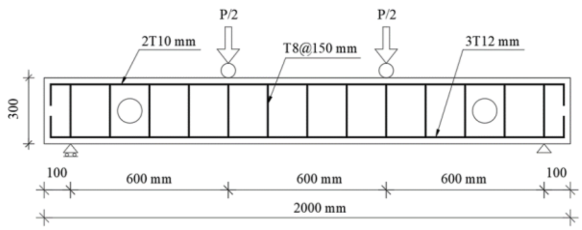


Figure 17. Test setup and reinforcement details [41]

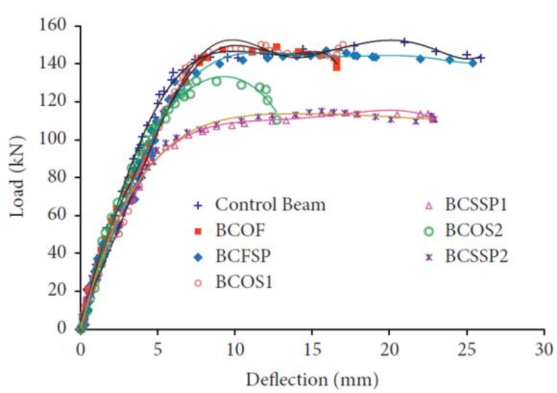


Figure 18. Load-deflection response of beam specimens [41]

The authors mentioned that all test specimens experienced similar initial stiffness values. However, the ultimate capacity of the beam was highly affected by the number of openings. More specifically, beams with two openings in the shear zone exhibited a reduction in strength by 13% compared to the control beam. In contrast, beams with an opening in the shear zone achieved approximately 97% of the control beam's strength. The steel plate was able to reduce the number of cracks in the strengthened beams compared to their counterparts. Moreover, the ductility of the beams with the opening in the shear zone was significantly enhanced when using steel plate as a strengthening material compared to the unstrengthened beam.

6.4 Beams with Openings Strengthened with Textile Reinforced Concrete (TRC)

A study by Abdul-Hamid et al. investigated the effect of strengthening RC beams with openings using Textile Reinforced Concrete (TRC) [42]. A total number of six specimens were tested experimentally under four-point loading. All beams have the same dimensions of 200 x 250 x 1700 mm (width x depth x length). Beams' details and test parameters are described in Figure 19.

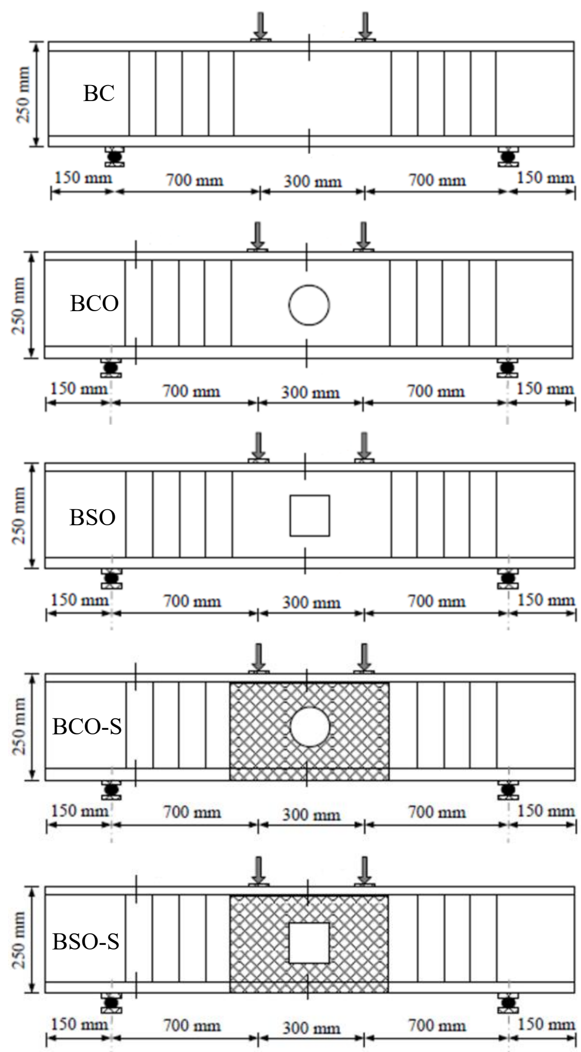


Figure 19: Specimens' geometry and reinforcement details [42]

One beam was set as a reference beam, while two beams were cast with a circular and square opening, respectively. Another three beams were strengthened with TRC and compared with their counterparts. The test results showed that the control beam achieved the highest load-carrying capacity and ductility among all specimens. In addition, it can be noticed that beams with an opening exhibited a significant reduction in strength and stiffness resulting from the loss in the concrete cross-sectional area due to the presence of the opening. Moreover, strengthening those beams with TRC was able to compensate for that loss. Additionally, specimens with different opening shapes showed an insignificant change in the ultimate capacity. However, different crack patterns were noticed near the square and circular openings. Specifically, vertical cracks were observed at the circular opening, whereas diagonal cracks towards the square opening corners were seen. Test results of all test specimens are shown in Table 5. It is worth mentioning that using TRC significantly reduced the number of cracks and deflection values compared to unstrengthened beams, as shown in Figure 20.

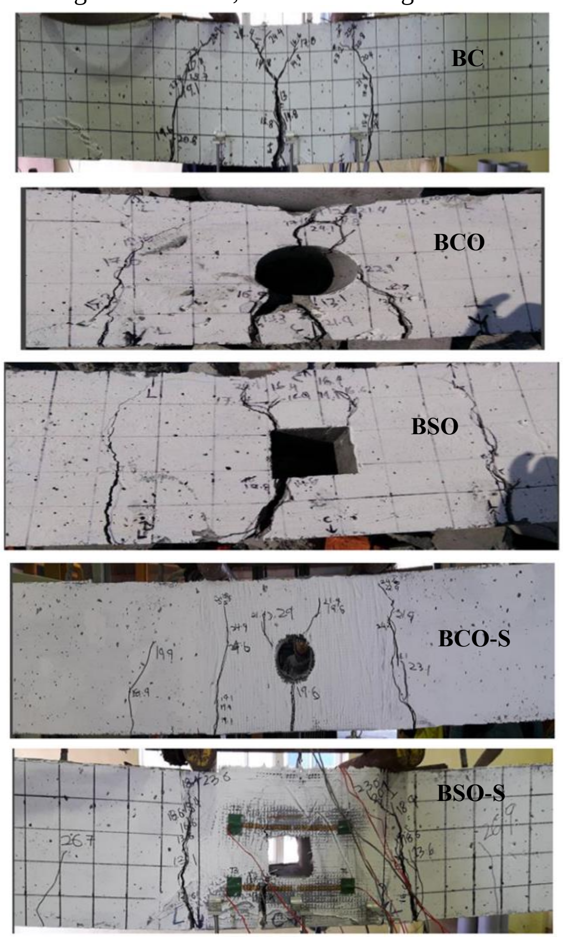


Figure 20: Failure mode and crack patterns for all test specimens [42]

Table 5: Test results for specimens [42]

Beam	Ultimate Load (kN)	Deflection (mm)	Failure Mode
BC	27.4	22.6	Flexure
BCO	25.7	17.3	Flexure
BSO	26.7	17.3	Shear failure
BCO-S	31.5	20.6	Flexure
BSO-S	28.7	17.6	Shear failure

6.5 Beams with Openings Strengthened with Bamboo Fiber Reinforced Composites (BFRC)

Chin et al. presented in their study the structural behavior of 14 test specimens [43]. The test parameters included the presence of openings in the shear zone and strengthening configuration. Beams were divided into two main groups, as shown in Table 6. The first group that contains openings is our concern in this review study. Three resins were used in the mentioned study to glue the BFRC plates into the concrete face; epoxy, vinyl-ester, and polyester. All beams were tested under four-point loading. Unstrengthened specimens with openings in the shear zone exhibited a significant reduction in strength by 54% compared to the control beam, as shown in Figure 21.

Table 6: Test specimens' details [43]

Group	ID	Strengthening type
A	CB	-
	BUO	Shear strengthening
	EBSO	
	PBSO	
	VBSO	
B	CB	-
	BUF	Flexural strengthening
	EBSF	

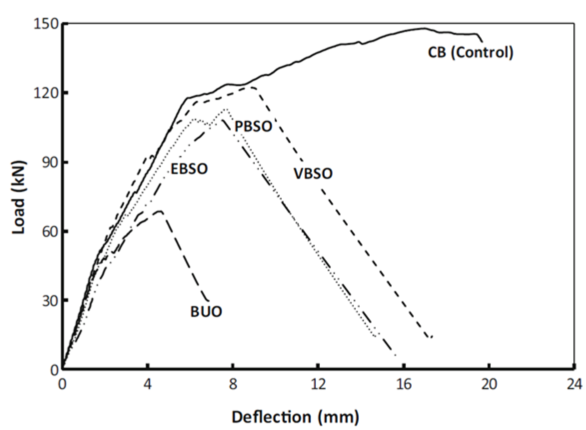


Figure 21: Load-deflection response of test specimens in group A [43]

Furthermore, strengthening that beam with BFRC plates was able to regain the load-carrying capacity to 34% higher than the unstrengthened specimen. However, when comparing the strengthened beams with the control one, the enhancement due to BFRC plates helped the beam to compensate for approximately 70% of the control beam strength. The beam with epoxy-based BFRC plates showed the best structural performance compared to other resins. In addition, using BFRC plates led to a significant enhancement in crack patterns, as depicted in Figure 22.

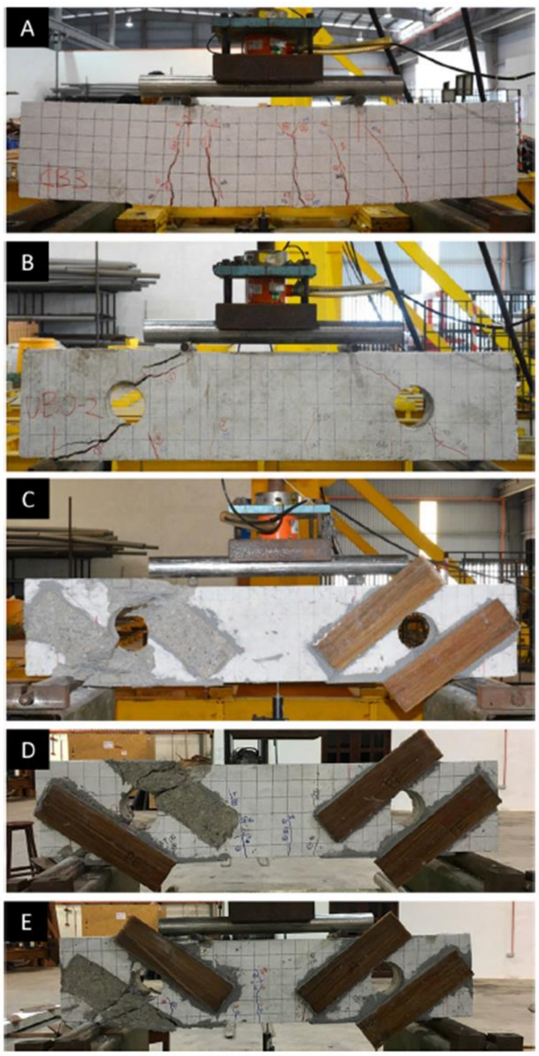


Figure 22: Crack patterns of test specimens in group (A). A: CB, B: BUO, C: EBSO, D: PBSO, E: VBSO [43]

6.6 Beams with Openings Strengthened with Ferrocement

Shaheen et al. investigated the effect of using a ferrocement layer as a strengthening technique for beams with openings [44]. This study used two types of ferrocement mesh: welded wire mesh and expanded steel mesh. In addition, the number of ferrocement layers was another important parameter in their study. All beams were with dimensions of 100 x 200 x 2000 mm (width x depth x length, respectively) and tested under four-point loading, as described in Figure 23. Table 7 displays the test results, including the ultimate load and ductility index, for all test samples. The highest ductility ratio was recorded by B10, which has only one opening at the right side of the beam and is strengthened with one layer of expanded metal mesh. In contrast, beam B1, which has no opening and was strengthened using two welded wire mesh layers, exhibited the highest energy absorption. The authors mentioned that the larger number of ferrocement layers, the higher cracking and ultimate loads and the higher the absorbed energy of test specimens. In addition, it is worth mentioning that the ferrocement layers were able to mitigate the concentrated stresses around the opening, which in turn led to preventing the concrete cover from spalling at failure. Last, the authors concluded that strengthening RC beams with openings using ferrocement layers significantly impacts the economic and durability merits that make it an alternative to traditional strengthening techniques such as RC jacketing. Also, they recommended future studies using different mesh reinforcement (e.g., polypropylene and Tenax mesh) [44].

Table 7: Test results for all specimens [44]

Beam No.	Ferrocement mesh	P_{ult} (kN)	Ductility Ratio
B1	Welded (2 layers)	63	1.911
B2	Expanded (1 layer)	58	2.71
B3	Expanded (1 layer)	54.3	2.2
B4	Expanded (1 layer)	14.7	2.37
B5	Welded (2 layers)	16.4	2.23
B6	Welded (3 layers)	22	1.88
B7	Expanded (2 layers)	25	2.36
B8	Expanded (1 layer)	25	2.88
B9	Welded (2 layers)	18	2.75
B10	Expanded (1 layer)	28	2.89
B11	Welded (2 layers)	28	2.27
B12	Welded (2 layers)	59	2

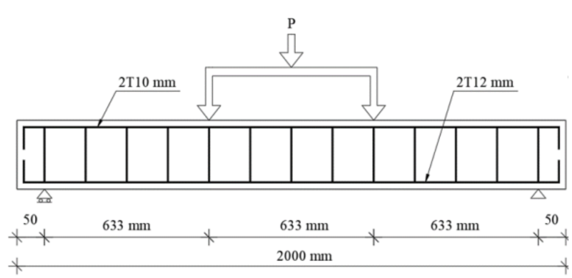


Figure 23: Test setup and specimens' details [44]

6.7 Beams with Openings Strengthened with Precast Strain-Hardening Cementitious Composites (SHCC) plates

Hassan et al. investigated the effectiveness of a new strengthening material called strain-hardening cementitious composites (SHCC) in RC beams with an opening [45]. A total of 10 beams were tested under four-point loading in order to understand the structural behavior of strengthened beams. Figure 24 depicts the details of the test specimens. The test parameters included the opening length and strengthening material. Precisely, the opening was placed at the mid-shear span with a width of 100 mm and three different lengths; 150, 300, and 450 mm, as displayed in Table 8. Three beams were strengthened with a steel wire mesh embedded inside the 20 mm SHCC plate. The main reason for adding this wire mesh is to enhance the ductility and cracking behavior of SHCC plates. Another three beams were strengthened with 20 mm of SHCC plate without adding steel wire mesh. The experimental results exhibited an excellent enhancement for strengthened beams in terms of ultimate load, ductility, and crack patterns. However, the improvement slightly reduces with increasing the opening length.

Table 8: Experimental test matrix [45]

ID	Lo (mm)	Strengthening type
BC	-	-
B_{150}	150	-
B_{300}	300	-
B_{450}	450	-
$B_{150,S}$	150	SHCC
$B_{300,S}$	300	SHCC
$B_{450,S}$	450	SHCC
$B_{150,S,R}$	150	SHCC with steel wire mesh
$B_{300,S,R}$	300	SHCC with steel wire mesh
$B_{450,S,R}$	450	SHCC with steel wire mesh

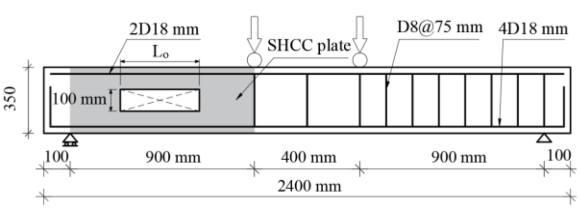


Figure 24: Details of test specimens [45]

Figure 25 shows that the strengthened beams with SHCC plate with embedded steel wire mesh achieved smaller shear crack width, which emphasizes the significant contribution of the steel wire mesh in enhancing the SHCC plates. Furthermore, the research results showed that the SHCC plates have a great impact on the serviceability limits of RC beams with an opening. The authors also compared the experimental findings with the analytical equations mentioned in both ACI 318-19 and JSCE standards for predicting shear capacities. They found a good agreement between the experimental results and the predicted shear capacities [45].

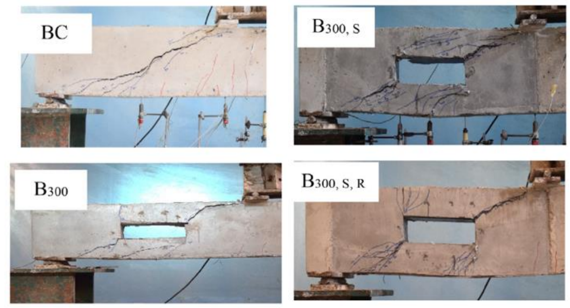


Figure 25: Crack patterns at ultimate load for test specimens [45]

6.8 Beams with Openings Strengthened with Shape Memory Alloy (SMA)

Aghayari et al. presented a novel strengthening method for RC deep beams using shape memory alloy (SMA) [46]. SMA is a promising material that has the ability to memorize its shape. In other words, it deforms upon cooling and returns back to its original undeformed shape upon heating. This new material has been used in several applications. In fact, the idea behind this phenomenon is based on the metallurgical effect of iron, which allows several transformations between iron phases, as demonstrated in Figure 26.

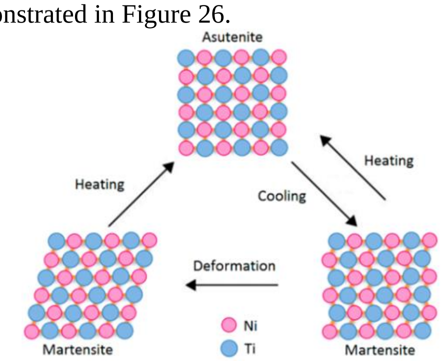


Figure 26. Martensite-Austenite transformation phases [47]

For example, the martensite phase, which is more favorable in a cold environment, transforms to the austenite phase upon heating as the last prefers high temperatures [47]. The authors, in their research, compared the use of FRP and SMA in strengthening. The test specimens had the dimensions of 0.6 x 2.0 x 5.5 m (width x depth x length), while the opening width and length were 0.3 and 1.0 m, respectively. The research included three specimens; one with an opening without strengthening as a control, and the other two samples had the same opening size but strengthened with FRP and SMA, respectively.

Figure 27 depicts the load-deflection response for test specimens. It can be noticed that the beam strengthened with FRP around the opening was able to obtain approximately 50% higher ultimate load compared to the control beam. Moreover, the beam strengthened using SMA achieved around twice the control beam's load-carrying capacity, indicating the significant effect of using SMA as a strengthening material [47].

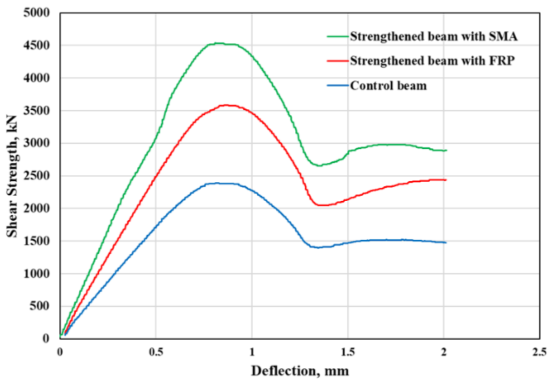


Figure 27. Load-deflection response of test specimens [46]

6.9 Effect of Opening Location, Size and Shape

A study by Saeed investigated the effect of changing the opening location along the beam length on the structural response of RC beams with openings [48]. Also, it discusses the impact of different shapes of the opening on the test specimens in terms of ultimate load and corresponding deflection values. A total number of 27 beam specimens with dimensions of 120 x 250 x 2000 mm (width x depth x length) were tested under four-point loading. Figure 28 depicts the geometry of test specimens. The test parameters were the opening location, size, and shape. The authors mentioned that varying opening size significantly affects the load-carrying capacity of beams with a circular opening at the shear span. For instance, Figure 29 shows the reduction occurred due to increasing the shear opening from 60 to 140 mm. Besides, the authors reported that the effect of opening location was significant. More specifically, a great effect could be observed when the opening was placed at shear span, while a more negligible effect was noticed for beams with the opening at flexure span. Therefore, the authors recommended the flexure span as the best place to make an opening in RC beams. Moreover, they reported that the beams with circular openings showed the best structural performance compared to those with square or rectangular openings. This could be attributed to the relatively higher concentration stresses that were generated around the square and rectangular openings. Additionally, the small opening at the flexure span decreased the ultimate load by 1.5%, whereas the large opening at the flexure span reduced the load-carrying capacity by 10%. On the other hand, RC beams with a small opening at shear span decreased the ultimate load by around 2.5%, while the test specimens with a large opening at shear span showed a reduction in strength by approximately 64%. Hence, RC beams with an opening at shear span are more critical than flexure span. Similar experimental findings were observed and reported numerically by Mansour [49].

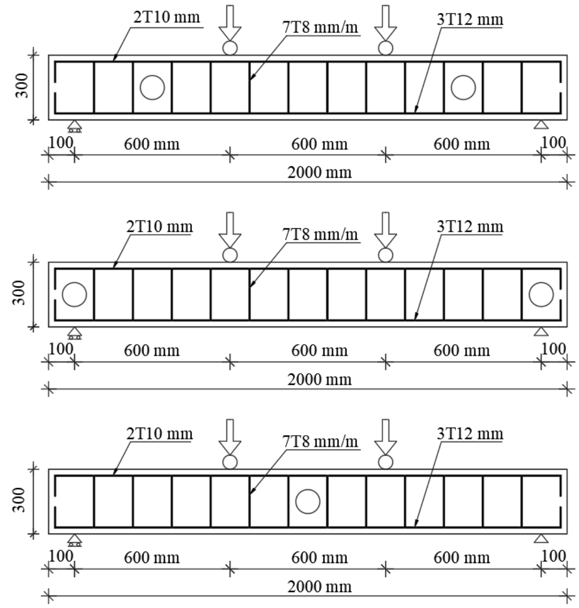


Figure 28: Reinforcement and geometry details of test specimens [48]

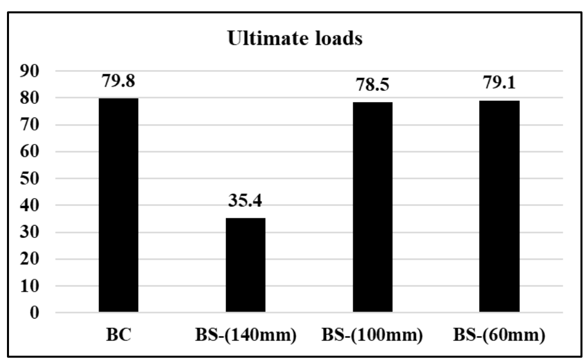


Figure 29: Effect of circular opening size on ultimate failure load [48]

6.10 Numerical Investigations

Investigating the effect of web opening on the behavior of the beam has gained much interest from researchers. However, in recent decades, numerical modeling using nonlinear finite element analysis software helped simulate the overall response of reinforced concrete beams. Therefore, several research studies investigated different parameters through numerical analysis to save effort, cost and time. For example, Sayed studied numerically the effect of vertical circular web opening in RC beams through modeling 41 beams with different parameters using ANSYS software [50]. Solid65 and solid186 elements with eight nodes were used to simulate the concrete and steel plates, respectively. In contrast, the link180 bar element was adopted to simulate the reinforcement. He concluded that the opening diameter has a more significant effect on the response of the beam rather than the number of openings.

Another study by Nie et al. assessed the best modeling technique for RC members using ABAQUS software [51]. CPS4R element with four nodes was used to simulate the concrete, and the T2D2 element was adopted to model the internal and external reinforcement. The cohesive layer was simulated using the COH2D4 element. The authors reported that the concrete damage plasticity model exhibited better numerical results comparable to the experimental results for beams that failed in a flexural manner. On the other hand, beams that failed in shear should be modeled using the brittle cracking model.

Elsanadedy et al. carried out an experimental and numerical investigation on RC beams with large rectangular web openings near the support [52]. LS-DYNA software was adopted in their study. 3D hexahedron element was used to simulate the concrete, whereas the Hughes-Liu beam element was adopted to model the reinforcement. The authors recommended using FRP strengthening technique in order to restore the loss in strength completely and partially restore the recorded loss in stiffness in case of large openings. In contrast, they recommended not using any strengthening technique for small openings as the reduction in strength and stiffness was negligible. El-Sisi et al. conducted an experimental and numerical investigation on 13 RC beams; one as control including no opening, six beams with the opening at flexure span, and the other six beams with the opening at shear span [53]. They also investigated the effect of CFRP on compensating for the loss in strength and ductility of test specimens under blast loading. ANSYS software was adopted in the numerical analysis. Eight-node SOLID65 and BEAM186 were used to simulate the concrete and the reinforcement, respectively. CONTA174 was adopted to represent the epoxy layer. They found that the adopted strengthening technique was able to recover the loss in strength up to 46% for beams with an opening at flexure span. In the end, they recommended avoiding drilling any opening at the shear span since it significantly reduces the overall beam response.

Mansour studied the shear behavior of continuous RC beams numerically with web openings using ABAQUS software [49]. He simulated the concrete, the reinforcement, and the cohesive layer using T2D2, CPS4R, and COH2D4 elements. He concluded that having a web opening inside the beam reduced its performance. Nevertheless, strengthening the opening using FRP sheets could restore the beams' capacity. Similar recommendations were mentioned by Nie et al. but for simply-supported beams having rectangular web openings and strengthened with externally bonded FRP [54].

7. Conclusions

This paper reviewed some recent studies related to openings in RC beams. Based on the previous review and discussion, the following conclusions and recommendations for future work could be drawn:

- Large openings in RC beams have to be considered in preliminary design stages to avoid undesirable failure of beams.
- It is highly recommended to avoid drilling any opening at the shear span of RC beams without adopting the proper strengthening technique based on engineering calculations.
- Small openings in flexure zone can be neglected in limit state design; however, it can significantly affect the serviceability limit state.
- RC beams with openings in the shear zone fail in a more brittle way and result in losing much strength and ductility than in the flexure zone.
- Circular openings showed less loss in the overall beam performance compared to other shapes (e.g., square and rectangular openings) as the flow of stresses around circular openings is much easier.
- Horizontal web openings are more recommended than vertical openings in RC beams as the last lead to a significant drop in the load-carrying capacity.
- Some strengthening techniques such as ferrocement and SHCC exhibited better ductility recovering of RC beams with openings than other methods. In contrast, regarding strength recovering, strengthening approaches such as SMAs and FRP gain more strength at the expense of ductility. Hence, the structural engineer should be aware of the target recovering terms before choosing the proper strengthening technique.
- The numerical investigations showed a good agreement with experimental results of RC beams with web opening, which could be adopted for future parametric studies.
- There is a gap in the experimental research concerning the repairing effect on beams damaged due to openings, so it is recommended to conduct related experimental investigations.

- Additionally, future research studies have to investigate the structural behavior of RC beams with openings subjected to dynamic loadings.
- The authors recommend developing new strengthening techniques to facilitate the construction process of beams with web openings.

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