A State-of-the-Art-Review on Performance RC Beams with Openings

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Abstract - The inclusion of web openings in reinforced concrete (RC) beams has become increasingly necessary to accommodate utility services like electrical wiring, plumbing, HVAC systems, and network cables. However, these openings significantly influence both the serviceability and strength of RC beams. In the service stage, they reduce stiffness, leading to increased deflection. At the ultimate stage, they cause stress concentrations due to the disruption of stress flow around the opening area. This geometric discontinuity can lead to premature failures if not properly addressed. Researchers have proposed various methods to counteract the reduction in strength and stiffness caused by openings. This paper reviews recent developments in the behavior and strengthening of RC beams with web openings. Openings are classified based on size, shape, position, orientation, and the stage at which they are introduced. Typical failure modes, such as flexural and shear failures, are also discussed. Among different shapes, circular openings perform better due to smoother stress distribution. Beams with openings in the flexural region generally show improved behavior compared to those in shear zones. Strengthening techniques using ferrocement and strain-hardening cementitious composites (SHCC) have proven effective. The study highlights the importance of considering web openings during the design phase to enhance structural performance and avoid unexpected failures.

***Key Words*: **Reinforced concrete beams, web openings, structural performance, serviceability, stress concentration, strengthening techniques.

1. Introduction

Incorporating openings within reinforced concrete (RC) beams has become essential in many buildings, particularly on service floors [1]. Architectural and mechanical engineers often face challenges due to floor height limitations, making it necessary for structural engineers to consider beam openings for accommodating utility ducts and pipes [1]. These openings facilitate the integration of various services, such as plumbing systems, telephone and internet cables, air-conditioning outlets, electrical wiring, and sewage pipelines [2–4]. Figure 1 illustrates a real-world example of an RC beam with a web opening used for such purposes. However, these openings introduce abrupt changes in geometry, which significantly influence the structural behavior of the beam element [5–9]. The stress flow is disturbed, leading to stress concentrations and potential weakening of the beam. To address these issues, numerous studies have proposed and evaluated different techniques for strengthening the areas around the openings in conventional RC beams [10–13]. The impact of an opening largely depends on its size and location, which play a crucial role in the beam's overall structural response. As a result, the study of RC beams with web openings has become a prominent topic of interest among researchers globally.

Figure 1: Illustration of utility openings integrated within RC beams in a real-world building scenario [14].

2. Objectives

The purpose of this review paper is to highlight the utilization and impact of openings in reinforced concrete (RC) beams, along with the advancements in this field. The key objectives include:

- To provide a comprehensive classification of different types of openings in RC beams
- To analyze the structural behavior of RC beams containing web openings
- To examine the common failure mechanisms associated with such beams
- To evaluate the influence of various strengthening techniques on the performance of RC beams with openings
- To review recent experimental and numerical investigations related to RC beams with web openings

3. Classification of Openings in RC Beams

Openings in reinforced concrete beams can be categorized based on several parameters, including their size, location, shape, and the time of execution.

3.1 Opening Size

Researchers have commonly classified openings in RC beams into small and large categories based on their dimensions [15]. Some studies have introduced an intermediate category, referring to such openings as medium-sized [16]. According to Somes et al., an opening is considered large if its depth exceeds 25% of the total web depth [17]. Alternatively, Mansur suggested that an opening should be classified as large if its clear length is greater than the thickness of the top or bottom chord members [18], as illustrated 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

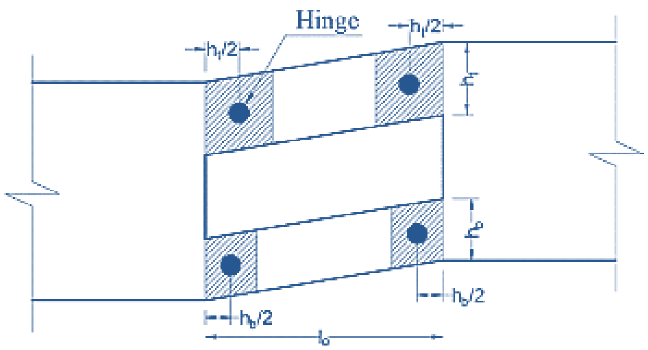


Figure 2: Categorization of RC beam openings based on their size dimensions [18].

This classification is rooted in the observation of plastic hinge formation at the four corners of the opening during beam failure, as highlighted by Mansur [19]. It's important to note that the determination of whether an opening is large or small should ideally be based on the overall structural behavior of the beam. If the RC beam with an opening still adheres to classical beam theory, the opening can be regarded as small due to its minimal influence. Conversely, if the presence of the opening alters the beam's behavior significantly, deviating from standard theory, it should be classified as large, warranting a more detailed structural assessment [19]. Despite this, practicing engineers typically rely on predefined classification methods for simplicity, without deeply analyzing the actual behavior of the beam.

3.2 Opening Shape

Openings in RC beams can also be categorized by shape, depending on their intended function. Amiri et al. [20] identified circular and rectangular openings as the most frequently used shapes in practical applications. Additionally, other forms—such as diamond, trapezoidal, triangular, and irregular openings—have been explored in research, as shown in Figure 3 [21]. Various design strategies and guidelines have been proposed to address the structural implications of these different shapes [22–27].

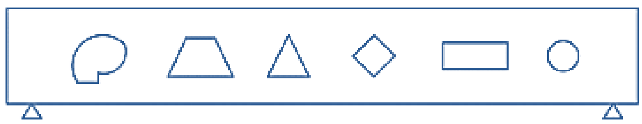


Figure 3: Categorization of RC beam openings based on their geometric shapes [21].

3.3 Opening Execution Time (Before/After Concrete Casting)

Openings in RC beams may either be incorporated during initial construction or introduced after the concrete has been cast. In some cases, modifications in the building's functionality—such as the need for new piping—necessitate cutting openings into already constructed beams. In such scenarios, appropriate strengthening methods must be applied to maintain structural integrity. Conversely, when openings are part of the initial design, they should be carefully accounted for in the early stages of structural planning, as emphasized by [28].

3.4 Opening Direction

The orientation of the opening within an RC beam is another critical classification factor. For instance, Abdul-Razzaq et al. [13] examined vertical openings located in the flange of beams and evaluated their impact on ultimate load capacity and deflection, as illustrated in Figure 4. Alternatively, Abdulrahman et al. [29] investigated horizontal openings, with their test configuration shown in Figure 5. Findings from both studies suggest that vertical openings tend to have a more pronounced effect on structural performance compared to horizontal ones. This heightened impact is likely due to the greater concrete removal from the compression zone in vertically oriented openings.

The structural response of beams with openings also varies depending on their position—whether near the support region (shear zone) or at the mid-span (flexure zone). Ali et al. [30] investigated the influence of opening location and concluded that shifting the opening away from the supports results in improved beam performance. Similar observations were made by Elsayed et al. [31], reinforcing the recommendation to position openings in regions dominated by flexure rather than shear.

Figure 4: Failure crack patterns observed in an RC beam featuring a vertically oriented circular opening [13].

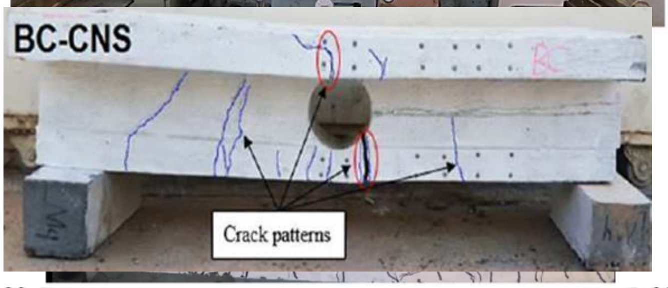


Figure 5: Crack development in an RC beam with a centrally located horizontal circular opening [29].

4. Guidelines for Selecting Opening Size and Location

Mansur and Tan offered practical guidance regarding the optimal sizing and positioning of openings in RC beams [32]. They advised limiting the opening depth to a maximum of 50% of the beam's overall depth (D) to avoid significant reduction in structural strength. Moreover, openings should be positioned at a minimum distance of 0.5D from supports, applied loads, or neighboring openings to avoid critical zones prone to congestion of reinforcement and high shear stresses. To improve serviceability and maintain the integrity of the top and bottom chord members, they recommended replacing a single large opening with multiple smaller ones of equivalent area. For T-beams, the most suitable position for openings is directly beneath the flange, which simplifies construction. Conversely, for rectangular beams, the typical placement is at mid-depth, although slight vertical adjustments are recommended. This ensures adequate concrete cover for lower chord reinforcements and preserves sufficient compressive material in the upper chord to prevent brittle failure.

5. Failure Modes

Various failure mechanisms are associated with RC beams that contain web openings [33, 34]. When small openings are introduced in the flexural region, they generally do not significantly affect the beam's strength, and failure tends to be ductile, as illustrated in Figure 6(a). However, larger openings in this region reduce the compression zone, typically resulting in crushing of the upper chord and a corresponding decrease in capacity, as shown in Figure 6(b). Openings located in the shear span, even if small, can cause more severe failure modes. Figure 7 highlights two such failure types: in beam-type failure, a crack propagates through the opening's center, while in frame-type failure, parallel cracks form on either side of the opening [32]. In cases involving larger shear-span openings, failure usually occurs by the formation of four plastic hinges at the opening's corners, resulting in a mechanism-type failure pattern, as depicted in Figure 8 [32]. Numerous studies have been conducted to better understand these behaviors under varying structural conditions [35, 36].

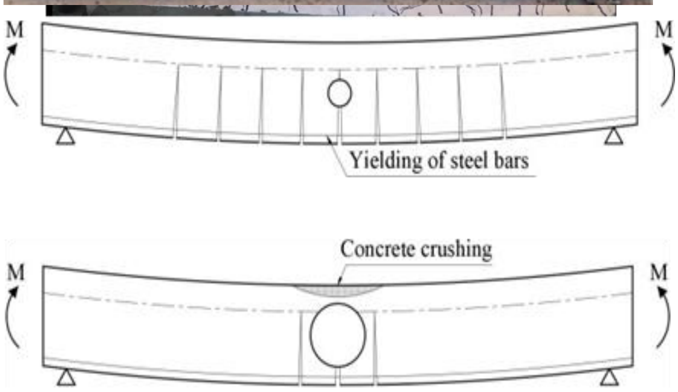
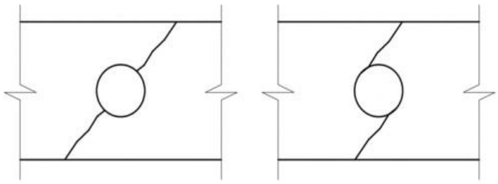


Figure 6: Schematic drawing showing failure modes of a beam with (a) small and (b) large openings in the flexure zone [32]



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

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

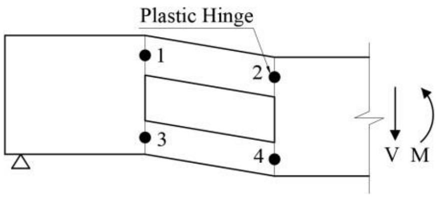


Figure 8: Collapse mechanism of beams with a large opening in the shear zone [32]

6. Recent Studies on Beams with Openings

This section highlights recent investigations into RC beams containing web openings and discusses various methods used to enhance their structural capacity.

6.1 Beams with Unstrengthened Openings

Daniel [37] explored the performance of RC beams featuring elongated web openings in response to the increasing demand from mechanical services to route utilities through structural elements. Recognizing that floors supported by beams in two perpendicular directions are increasingly used, Daniel carried out experimental tests on five RC beams under four-point bending conditions, as shown in Figure 9. The key variable in his study was the opening length, with corresponding details provided in Table 1. Results revealed that increasing the opening length led to reductions in both shear and flexural stiffness. Beams with longer openings exhibited a Vierendeel action, characterized by the formation of four plastic hinges at the corners of the opening, ultimately resulting in failure. In contrast, beams with shorter openings failed primarily through diagonal shear cracking.

Table 1: Details of test specimens [37]

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

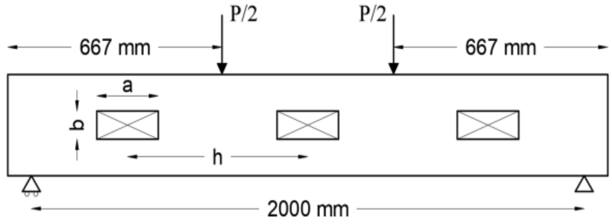


Figure 9: Representation drawing showing the test setup [37]

Figure 10 illustrates the load-deflection behavior of the tested specimens. It was observed that an increase in opening length led to higher deflection values at ultimate load. Daniel reported that longer openings notably reduced the strength and stiffness of the beams. Furthermore, a nonlinear finite element (FE) analysis was performed and validated against the experimental data. The numerical results showed strong agreement with the experimental findings, as highlighted by Daniel [37].

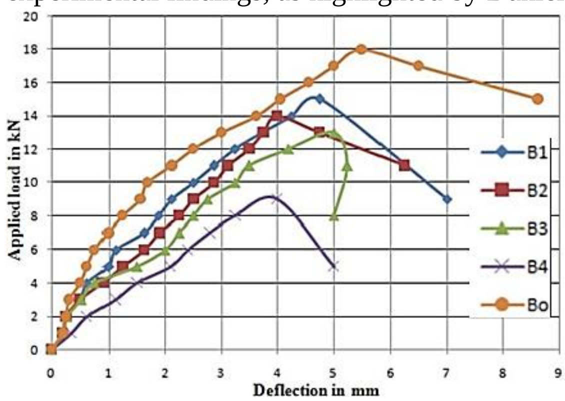


Figure 10: Load-deflection reply for test specimens [37]

6.2 Beams with Openings Strengthened with FRP

Nie et al. [38] conducted an experimental study on six large-scale inverted T-section beams with varying web opening sizes and locations to evaluate the effectiveness of different strengthening methods. Figure 11 presents the specimen details. The researchers preferred placing the flange in tension (inverted T-beam) to simulate negative bending conditions, which are more critical than positive bending. Their findings indicated that introducing openings in existing RC beams is practical when effective strengthening techniques are applied. They used fiber-reinforced polymer (FRP) sheets, which showed excellent results in restoring strength and ductility while being easy to install. As shown in Figure 12, unstrengthened beams experienced severe cracking and reduced load capacity. In contrast, FRP-strengthened beams displayed improved crack patterns and performance. Particularly, CFRP jackets combined with spike anchors significantly enhanced both strength and ductility. Additionally, the authors developed an analytical model to predict the flexural capacity of RC beams with small and medium openings, which showed good agreement with the experimental results [38].

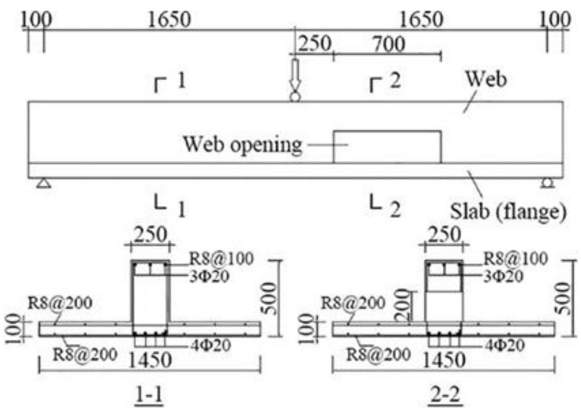


Figure 11: Details of test specimens [38]

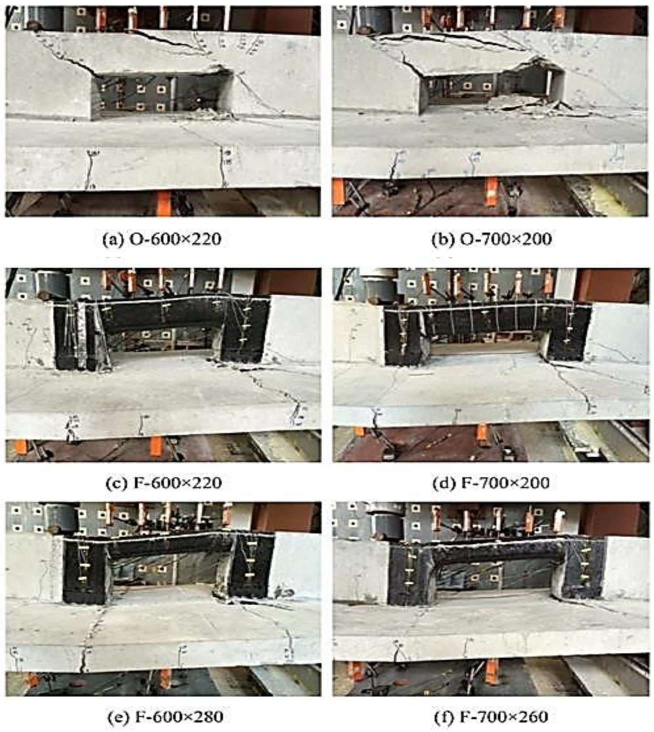


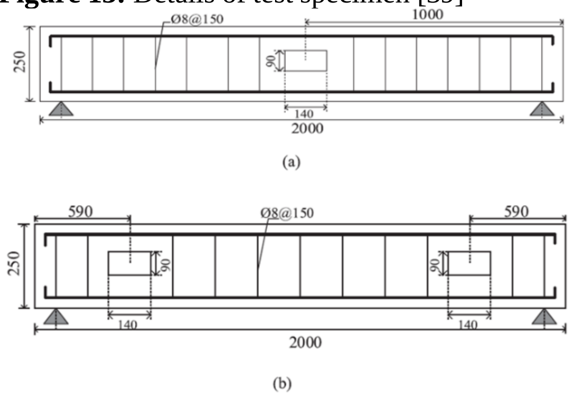
Figure 12: Failure modes of test specimens [38]

Salih et al. [39] experimentally studied RC beams with web openings located in the shear and flexural zones under cyclic loading. Figure 13 illustrates the specimen geometry, reinforcement details, and opening locations. CFRP sheets were applied as external strengthening methods, with two configurations: vertical and inclined wrapping, as summarized in Table 2. The study evaluated hysteretic load-deflection behavior, failure modes, energy dissipation, stiffness degradation, and ductility. The results demonstrated that the CFRP strengthening notably improved overall beam performance. Specifically, beams with shear-zone openings strengthened using CFRP showed a 63% increase in ultimate strength compared to the control beam, while those with flexural-zone openings showed a 73% strength gain. Figure 14 presents the stiffness degradation, revealing that inclined CFRP wrapping provided better stiffness retention than vertical wrapping for both shear and flexural openings [39].

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 developed a numerical approach to predict the experimental behavior of RC beams with openings using constitutive and concrete damage plasticity models [39]. These models successfully simulated the nonlinear mechanical properties of concrete, showing good agreement with experimental outcomes. The maximum error recorded was about 8% in deflection and 10% in load-carrying capacity. With verified accuracy, the models were further applied to study additional parameters such as the length of FRP sheets, opening size, and location. Based on these simulations, it was found that the placement and dimensions of openings significantly influence the structural response. Among various strengthening strategies, using a double layer of CFRP sheets proved to be the most effective in enhancing beam performance under the tested conditions. The authors concluded that this method ensures improved safety, especially for beams with large openings.

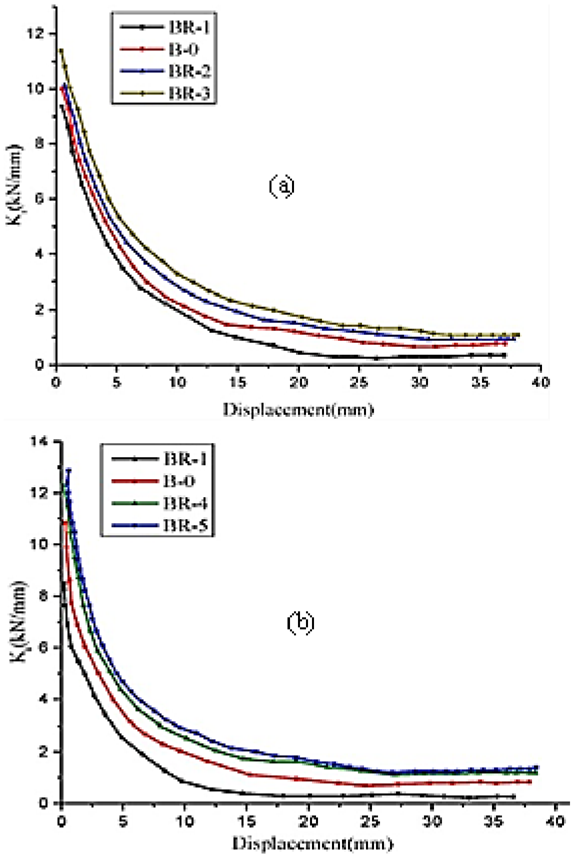


Figure 14: stiffness degradation for beams with opening in (a) shear zone and (b) flexure zone [39]

6.3 Beams with Openings Strengthened Using Bamboo Fiber Reinforced Composites (BFRC)

Chin et al. [43] investigated the structural performance of 14 reinforced concrete beam specimens, focusing on the influence of web openings and the effectiveness of BFRC strengthening. The study considered beams with openings located in the shear zone and evaluated different strengthening configurations. The specimens were categorized into two primary groups, as outlined in Table 6, with the group containing shear zone openings being the focus of this review. To bond the BFRC plates to the concrete surface, three types of resins—epoxy, vinyl-ester, and polyester—were utilized. All beams underwent four-point bending tests. Results indicated that unstrengthened beams with shear zone openings experienced a significant decrease in load-carrying capacity, showing a 54% reduction compared to the control specimen, as illustrated in Figure 15.

Table 3: Test specimens' details [43]

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

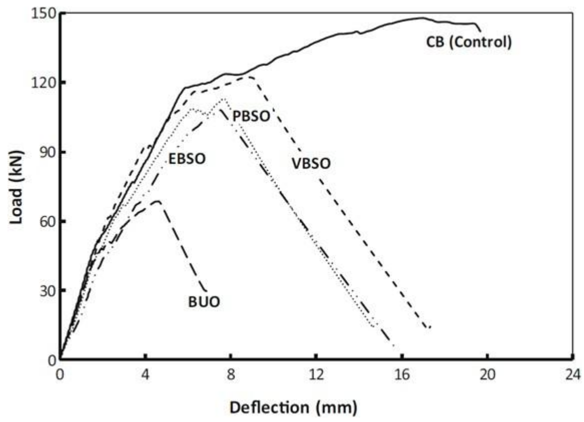


Figure 15: Load-deflection response of test specimens in group A [43]

The application of BFRC plates effectively improved the structural performance of beams with openings, restoring the load-carrying capacity to 34% more than that of the unstrengthened specimen. However, when compared to the control beam without openings, the strengthened beams achieved around 70% of its original strength. Among the different bonding resins tested, the epoxy-based BFRC plates demonstrated the most favorable performance. Additionally, the use of BFRC significantly improved the cracking behavior of the beams, resulting in more controlled and less severe crack patterns, as illustrated in Figure 16.

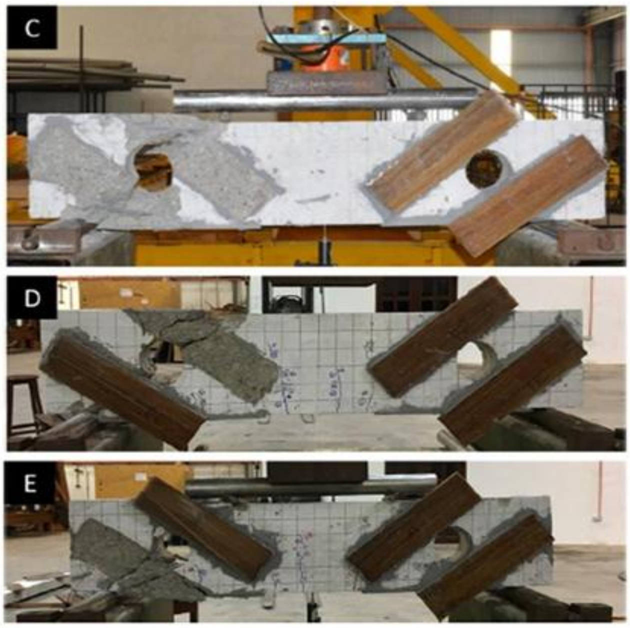


Figure 16: Crack patterns of test specimens in group (A). A: CB, B: BUO, C: EBSO, D: PBSO, E: VBSO [43]

6.4 Beams with Openings Strengthened Using Precast Strain-Hardening Cementitious Composite (SHCC) Plates

Hassan et al. [45] explored the performance of reinforced concrete beams with web openings strengthened using strain-hardening cementitious composites (SHCC). A total of ten beams were subjected to four-point bending to evaluate their structural response. Figure 24 shows the configuration of the tested specimens. The study considered two main variables: the length of the opening and the type of strengthening material. Openings were positioned at the mid-shear span with a fixed width of 100 mm and three lengths—150 mm, 300 mm, and 450 mm—as listed in Table 8. Three of the beams were reinforced with a 20 mm thick SHCC plate containing embedded steel wire mesh, intended to improve ductility and control cracking. Another set of three beams used SHCC plates without mesh reinforcement. The test results demonstrated a significant improvement in load-carrying capacity, ductility, and crack control for the strengthened beams. However, it was observed that the effectiveness of the strengthening slightly decreased as the opening length increased.

Table 4: Experimental test matrix [45]

ID	Lo (mm)	Strengthening type
BC	-	-
B150	150	-
B300	300	-
B450	450	-
B150,S	150	SHCC
B300,S	300	SHCC
B450,S	450	SHCC
B150,S,R	150	SHCC with steel wire mesh
B300,S,R	300	SHCC with steel wire mesh
B450,S,R	450	SHCC with steel wire mesh

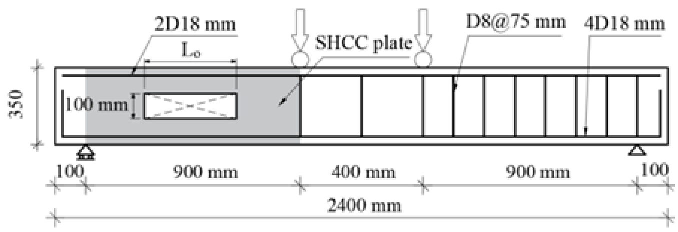


Figure 17: Details of test specimens [45]

As illustrated in Figure 18, the beams strengthened with SHCC plates incorporating steel wire mesh exhibited narrower shear cracks, highlighting the mesh's crucial role in improving the performance of SHCC plates. Moreover, the findings revealed that SHCC strengthening significantly enhances the serviceability of RC beams with openings. The authors also compared their experimental data with analytical shear capacity predictions from ACI 318-19 and JSCE design standards. The comparison showed a strong correlation between the experimental outcomes and the theoretical predictions [45].

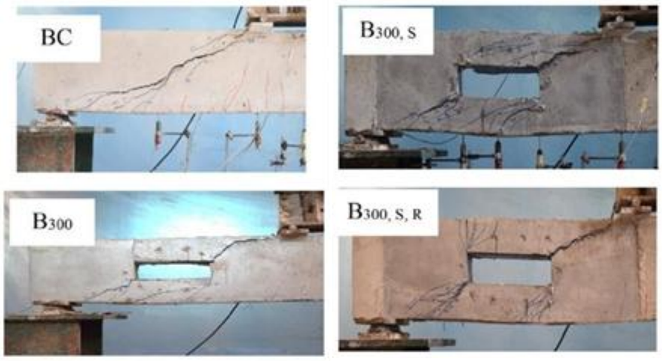


Figure 18: Crack patterns at ultimate load for test specimens [45]

7. Conclusions

This paper presented a comprehensive review of recent research on RC beams with web openings. Based on the findings, the following conclusions and future recommendations are drawn:

- Incorporating large openings should be addressed during the initial design phase to avoid structural failure.
- Avoid creating openings in the shear zone unless proper strengthening is applied based on engineering analysis.
- While small openings in the flexural zone may be ignored in ultimate limit state design, they can negatively impact serviceability.
- Openings in the shear region tend to induce brittle failures, causing greater losses in both strength and ductility compared to those in the flexural zone.
- Circular openings perform better than square or rectangular ones due to smoother stress distribution.
- Horizontal openings are preferable over vertical ones, which can significantly reduce load-bearing capacity.
- Numerical studies have shown strong correlation with experimental outcomes, supporting their use in future parametric analyses.
- There is a research gap regarding the repair of beams damaged due to openings, warranting further experimental exploration.
- Future studies should examine the behavior of RC beams with openings under dynamic loading conditions.
- Developing innovative strengthening techniques is recommended to simplify the construction process involving web openings.

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