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RC beams with web openings retrofitted by diverse techniques: A state of the art review

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Abstract. In order to accommodate necessary services like air conditioning, power, telephone, and computer network, the construction of modern structures requires the use of several pipes and ducts. The installation of these utilities is made possible through web openings in concrete beams. The strengthening of reinforced concrete (RC) beams can be accomplished in a modern and efficient way by using externally bonded fibre reinforced polymer (FRP) sheets, strips, or steel plates. Many investigations have been done on reinforced concrete beams having web openings. This state-of-the-art research on the behavior, analysis, and design of reinforced concrete (RC) beams with transverse web openings is summarized in the current study. The majority of research compared shear and flexural strengthening, while others investigated the effect of openings on shear and flexural separately with different loading. A variety of topics will be highlighted and discussed, including opening classification, opening location guidelines, and the structural behaviour of RC beams with web openings. Various design approaches will also be discussed in detail. Moreover, the use of Fibre Reinforced Polymer (FRP) material and steel plates to strengthen RC beams with openings is presented. Finally, future research directions based on the gaps in the current work are presented.

Keywords: RC beams, Web opening, Fibre Reinforced Polymer, Shear strengthening, Concrete and composite

1 Introduction

In many buildings, particularly in service floors, the inclusion of openings within reinforced concrete (RC) beams has become crucial. This is due to the limitation in clear height faced by architectural and mechanical engineers. Structural engineers must now consider these openings during the design phase to accommodate the passage of ducts and pipes. Various applications within the building necessitate the presence of such openings in the structural beams [1]. These include plumbing, telephone cables, air-conditioning outlets, internet connections, electricity wires, and sewage pipelines [2-4]. An example of RC beams with a web opening can be seen in Fig.1. The primary challenge with incorporating openings in RC beams is the sudden change in geometry, which significantly impacts the structural behavior of the element [5-9]. Several studies have been conducted to develop techniques for strengthening the region surrounding the opening in conventional concrete beams [10-13]. It is important to note that the location and size of the opening have a significant influence on its effect on the beam's response. Consequently, the study of RC beams with openings has garnered interest worldwide.

Fig. 1. Example of openings passing through RC beams in an existing building

2 Objectives

This review paper aims to condense the information on the use of openings in RC beams and their development factors into the following key points:

- Summarize the classification of openings in RC beams.
- Understand the behavior of RC beams with web openings.
- Discuss failure modes of RC beams with openings.
- Illustrate the effect of strengthening techniques on RC beams with openings.
- Present recent studies of RC beams with openings.

3 Classification of Openings in RC Beams

3.1 Opening Dimensions

Several studies classify openings into small, medium, and large sizes based on their dimensions [14,15]. Large openings are defined as having a depth exceeding 0.25 times the total web depth or a clear length greater than the maximum thickness of the top and bottom chord members [16,17]. This classification is determined by the formation of plastic hinges at the corners of the opening as explained by Mansur. However, the actual classification should consider the overall beam behavior, with small openings having a negligible effect and large openings requiring careful examination due to potential deviations from traditional beam theories [18]. Despite this, many structural design engineers rely on simplified classification techniques without considering the beam's actual behavior.

3.2 Opening Shape

Openings in RC beams are classified based on their shapes, including circular and rectangular shapes commonly seen in practice as Amiri et al. [19] indicated. Other shapes like diamond, trapezoidal, triangular, and irregular have also been studied [20]. Various design approaches and recommendations have been developed to accommodate these openings in RC beams [21–26].

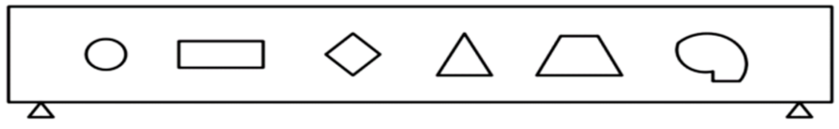


Fig. 2. Classification of opening in terms of shape [20]

3.3 Opening Direction

Openings in RC beams can be located in different positions. Vertical openings in the beam's flange were studied by Abdul-Razzaq et al. [13], while horizontal openings were investigated by Abdulrahman et al. [27]. Vertical openings have a more significant impact on the beam's response, attributed to concrete loss on the compression side. The location of the opening also affects beam behavior, with openings near the support differing from those near the mid-span. Ali et al. [28] and Elsayed et al. [29] found that placing openings away from the supports improves beam performance.

4 Guidelines for the Selection of Openings Location and Size

Mansur and Tan [30] recommended key guidelines for openings in RC beams. The opening depth should not exceed 50% of the beam depth (D) to avoid capacity reduction. Placing the opening at least 0.5D away from supports, loads, or other openings helps avoid critical zones. Dividing a long opening into multiple openings with equal area ensures serviceability and chord member stability.

5 Modes of Failure

The failure modes of beams with openings were discussed, revealing different behaviors [31, 32]. Small openings in the flexure zone have negligible effects on strength and exhibit traditional ductile failure [Fig. 3(a)]. Conversely, large openings in the flexure zone reduce concrete in compression, diminishing ultimate capacity and leading to concrete crushing of upper chord members [Fig. 3(b)]. Beams with openings in the shear span exhibit various failure scenarios. Small openings result in tension diagonal failure, either as a single crack passing through the center of the opening (beam-type) or two parallel cracks on opposite sides of the opening (frame-type) [Fig. 4]. Large openings typically fail in shear, forming a mechanism with four plastic hinges at corners [30]. Numerous studies have investigated the behavior of RC beams under different conditions [33, 34].

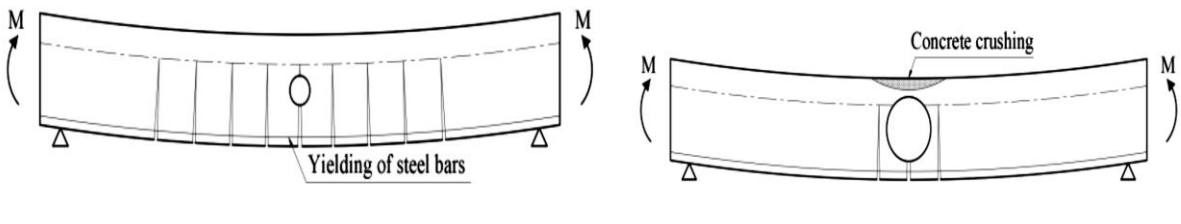
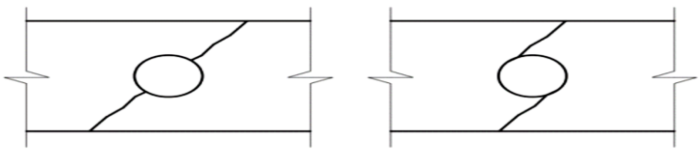


Fig. 3. Schematic drawing showing failure modes of a beam with (a) small and (b) large openings in the flexure zone [30]



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

Fig. 4. Shear failure modes of beams with a small opening [30]

6 Beams with Openings: Recent Studies

This section highlights recent research studies on RC beams with web openings. It also discusses various strengthening techniques employed to address the strength loss in these beams.

6.1 Beams with Unstrengthened Openings

Daniel conducted a study on RC beams with elongated openings, investigating the effect of opening length on beam behavior [35]. Increasing the opening length reduced shear and flexural modulus. Beams with large openings exhibited Vierendeel action with four plastic hinges, leading to failure. Smaller openings resulted in diagonal shear cracks and failure.
Fig. 6 displays the load-deflection response of the specimens. Longer openings corresponded to higher deflections at ultimate. Daniel found that increased opening length led to a significant decrease in strength and stiffness. The study also validated its findings through a successful nonlinear FE analysis [35].

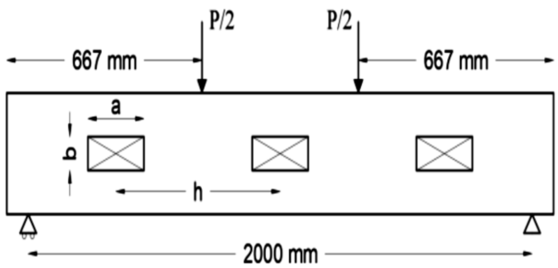

Fig. 5. Schematic drawing showing the test setup [35]

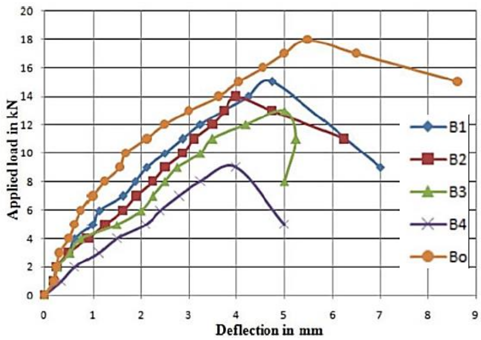

Fig. 6. Load-deflection response for test specimens [35]

6.2 Beams with Openings Strengthened with FRP

A recent study by Elansary et al. in 2022, the shear behavior of reinforced concrete beams with a web opening was investigated experimentally [36]. Six beams of varying opening sizes were tested using a four-point loading method. The reinforcement details and dimensions of the beams can be seen in Fig. 7. The results showed a significant reduction of around 35% in the beam with a large opening compared to the control beam. However, when the opening was reinforced with CFRP sheets, an average increase of 25% was observed compared to the unstrengthened beams. The cracking pattern and failure modes for the six beams are illustrated in Fig. 8. Specimen B6 demonstrated the effectiveness of the strengthening technique, with a diagonal shear crack near the support away from the opening at the point of failure [36].

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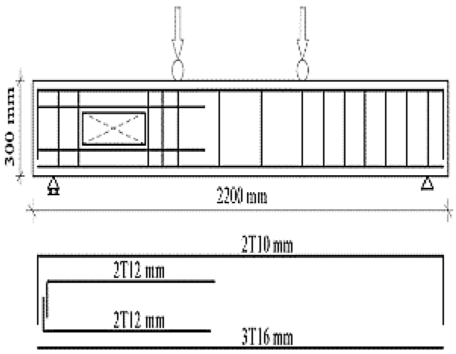

Fig.7. Specimen fabrication and geometry details [36]

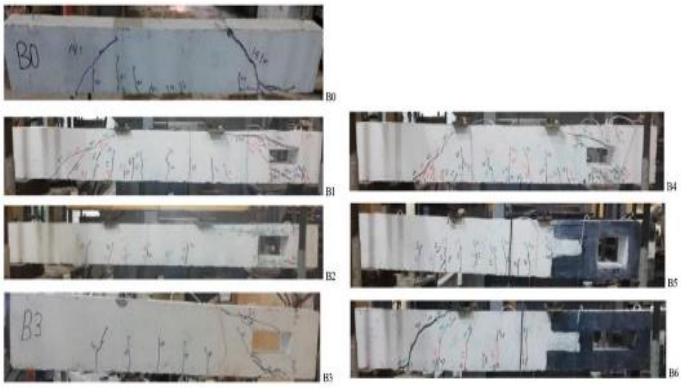

Fig.8. Crack patterns and failure modes [36]

6.3 Beams with Openings Strengthened with Steel Plates

Robert et al. [37] examined steel plates as a strengthening method for beams with openings. They conducted experiments on seven beams, measuring 150 mm in width, 300 mm in depth, and 2000 mm in length in Fig. 9 and reinforced them with longitudinal bars and stirrups. The experiments, using a four-point loading setup, explored different test parameters such as flexure zone openings, shear zone openings, and multiple shear zone openings. Detailed test parameter information can be found in Fig. 10 illustrates the load-deflection behavior of the specimens.

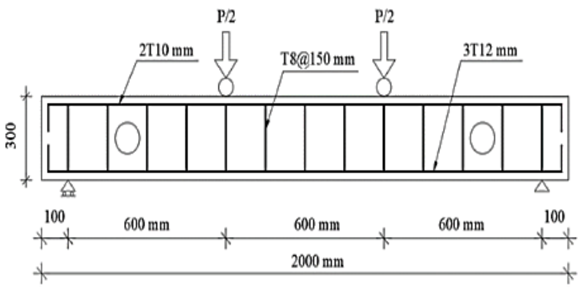

Fig.9. Test setup & reinforcement details [37]

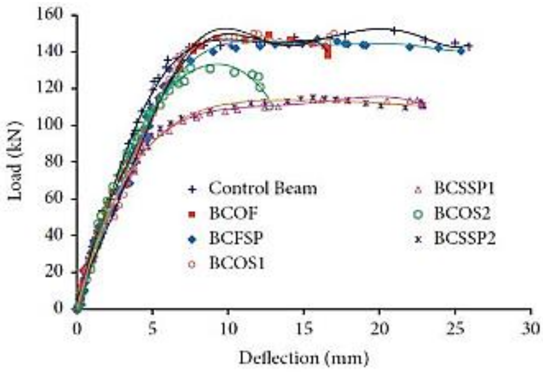

Fig.10. Load-deflection response [37]

The authors found that all test specimens had similar initial stiffness values. However, the number of openings significantly affected the ultimate capacity of the beams. Beams with two shear zone openings showed a 13% strength reduction compared to the control beam, while beams with a single shear zone opening achieved approximately 97% of the control beam's strength. The use of steel plates as strengthening material reduced cracks in the reinforced beams and enhanced ductility in the presence of a shear zone opening, surpassing the performance of the unstrengthened beam.

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

Hassan et al. [38] investigated the effectiveness of strain-hardening cementitious composites (SHCC) in strengthening RC beams with openings. Ten beams were tested under four-point loading, examining the impact of opening length and strengthening material. The experimental results showed significant improvements in ultimate load, ductility, and crack patterns for the

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strengthened beams. However, the degree of improvement slightly decreased with increasing opening length.

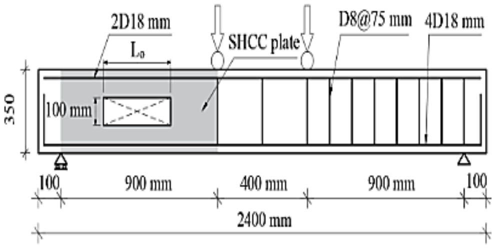

Fig.11. Details of test specimens [38]

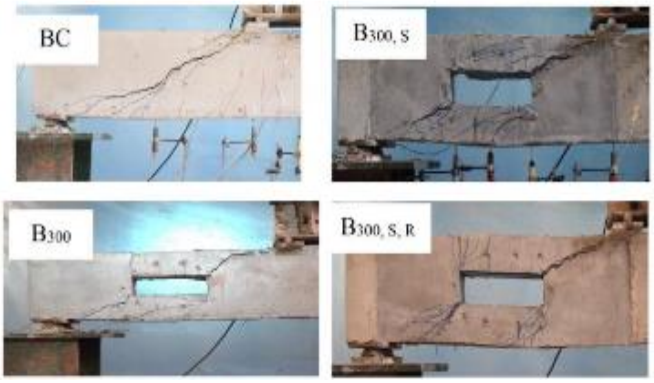

Fig.12. Crack patterns at ultimate load [38]

6.5 Effect of Opening Location, Size and Shape

Saeed conducted a study [39] to examine how the structural response of RC beams with openings is affected by changes in opening location and shape. A total of 27 beam specimens were tested under four-point loading, with dimensions of 120 x 250 x 2000 mm. The results revealed that altering the size and position of the opening had a significant impact on the beams' load-carrying capacity. Circular openings demonstrated superior structural performance compared to square or rectangular openings. The study recommended placing openings in the flexure span rather than the shear span for optimal results. Moreover, it observed reductions in ultimate load for beams with small openings in either the flexure or shear span, and emphasized the heightened vulnerability of beams with openings in the shear span. These findings were consistent with numerical results reported by Mansour [40].

6.6 Numerical Investigations

Web openings in beam structures have attracted significant research attention, with numerical modeling providing an efficient approach for analysis. Sayed used ANSYS software to study circular web openings in RC beams, finding that opening diameter had a greater impact on beam response than the number of openings [41]. Nie assessed modeling techniques in ABAQUS, suggesting different models for flexural and shear failure [42]. Elsanadedy investigated large rectangular web openings, recommending FRP strengthening for large openings while small openings required no additional strengthening [43]. Mansour's numerical study on continuous RC beams with web openings demonstrated a negative impact on performance, but FRP sheet strengthening could restore their capacity [40].

7 Conclusion

After reviewing recent studies on openings in RC beams, several conclusions and recommendations can be made:

- The presence of web openings in RC beams has a significant impact on their structural behavior and performance.
- The diameter of the opening is found to have a more substantial influence on beam response compared to the number of openings.

- Strengthening techniques, such as using FRP sheets, can help restore the capacity and performance of beams with openings.
- The location of the opening within the beam also plays a crucial role in the beam's response, with openings in the shear span having a more detrimental effect.
- The choice of modeling technique, such as concrete damage plasticity or brittle cracking models, should be based on the failure mode observed in experimental or numerical investigations.
- Further research is needed to explore additional parameters and factors influencing the behavior of beams with openings, such as different opening shapes, reinforcement configurations, and load types.
- Experimental validation of numerical models and findings is essential to ensure the accuracy and reliability of the proposed strengthening techniques.
- 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.

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