SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I2P108

Volume 12 Issue 2, 79-88, February 2025

Review Article

A Review Paper on Various External Strengthening Techniques for Reinforced Concrete Deep Beam with Openings

Rakesh Shivaji Mawal[1], Govardhan Bhatt[2]

[1,2]*Department of Civil Engineering, NIT Raipur, Chhattisgarh, India.*

[1]*Corresponding Author : rakesh.mawal1991@gmail.com*

Received: 13 December 2024 Revised: 12 January 2025 Accepted: 11 February 2025 Published: 27 February 2025

Abstract *- In structural design, deep beams are essential for carrying large loads and preserving overall stability. These days, it is common to find Reinforced Concrete (RC) deep beams constructed with circular or rectangular apertures to pass electrical cables, plumbing pipes, and air conditioning ducts. The beam's stiffness and strength may be diminished due to these openings and increasing deflection and breaking. The opening's geometric discontinuities cause the nonlinear distribution of stress across the beam's depth to be disturbed. Numerous researchers have examined how these opening dimensions and shapes affect how deep beams perform structurally. Hence, many researchers use external strengthening techniques to enhance the structural performance of a beam by adding additional reinforcement materials to the outside. This review aims to evaluate the impact of various external strengthening methods like Carbon Fiber Reinforced Polymer (CFRP), galvanized flat and corrugated steel sheets, glass fiber reinforced polymer, and a plate of metals on the deep beams made of RC with openings. Furthermore, recommendations for future research are proposed to fill the gaps observed in the current body of knowledge.*

Keywords *- Strengthening, Deep beam with openings, Shear, CFRP, Galvanized steel sheet.*

1. Introduction

The effective reinforcement and strengthening of concrete components are necessary in structural engineering to guarantee the civil infrastructure's robustness and structural stability. A deep beam generally has a short span relative to its depth. Indian standard 456-2000 [28] defines a flexure member having a proportion of span and depth less than two, which is referred to as a deep beam; the same definition given by the Canadian Standard Association [27], ACI [26] considered this value less than four. The variations in these definitions illustrate how different standards and regions may enforce unique requirements for the proportion of span and depth of deep beams. Although the definitions vary, it is commonly understood that deep beams cannot be designed with the same assumptions as normal beams, especially the belief that the plane section stays plane during bending. Consequently, over the last 70 years, researchers have thoroughly investigated the deep beam's shear behaviour. Since the necessity for deep beams has increased over the past 20 years, many deep beam design concepts have been offered in the most recent design documents, including the Euro code, ACI code, and British Standard Institute BSI, which offered few guidelines for building deep beams, particularly when those beams have intricate details like web holes [8]. Numerous experiments and theoretical models have contributed to enhancing the precision of the shear capacity of deep beams [1-3, 14, 15, 19, 20, 24]. In structural engineering, deep beams composed of reinforced concrete are frequently utilized. It offers several advantages for structural applications in high-rise buildings, warehouses, bridges, industrial facilities, basement levels, foundations, and particularly at transfer floors, where they help support heavy loads and maintain structural stability. As the depth of a deep beam is larger than a normal beam, it frequently requires openings to make room for vital systems like electrical cables, air conditioning ducts, computer network connections, and door and window access.

The needs of architectural and mechanical disciplines may also necessitate these openings, which often results in cracking, stress concentrations, and a higher risk of shear failure, all of which might eventually endanger the structure's integrity [12, 13] similar to a steel beam with openings [10, 11]. Numerous investigations have been carried out to look at how opening shape impacts the behaviour of the structure of deep beams [16-18, 21, 23]. As a result, it is essential to implement appropriate measures to reinforce the beam and restore its capacity due to the strength losses that occur when such openings are required. Materials like Fiber-Reinforced Polymer (FRP) made up of carbon and glass, as well as flat steel plates and galvanized corrugated sheets, are used to strengthen deep beams made of RC that have openings in them.

1.1. Relevance of the Study

Because of the growing need for effective and adaptable designs in buildings, bridges, and other infrastructure, strengthening RC deep beams with apertures has become a crucial component of contemporary structural engineering principles. The presence of apertures that are frequently necessary for utilities like cables, ducts, or pipelines can seriously impair their structural soundness and functionality. Therefore, it is essential to investigate efficient external strengthening methods that can improve or restore their ability to support loads. Developing new strengthening techniques is necessary because existing methods may not adequately reinforce beams with openings.

This review is highly relevant to today's engineering environment as it comprehensively analyses various external strengthening methods, helping engineers select the most suitable solutions for specific structural challenges. This study adds to the continuous development of RC deep beam building techniques by tackling the increasing demand for safe and long-lasting design, providing insightful information to both academic researchers and business practitioners.

1.2. Research Problem

Stress concentrations and dispersed load patterns in RC deep beams with apertures considerably reduce strength, stiffness, and shear capacity. Effective external strengthening solutions, such as glass fiber reinforced polymer, FRP, galvanized flat and corrugated steel sheets, and a plate of metal reinforcement, is necessary because traditional reinforcing techniques are frequently impractical. This study looks at a number of strengthening methods to identify workable solutions for enhancing and regaining the structural performance of RC deep beams with apertures.

1.3. Significance of Work

This paper comprehensively investigates external strengthening methods for RC deep beams with openings, addressing a significant structural difficulty in contemporary construction. In addition to helping to develop practical, cost-effective, and sustainable strengthening methods that guarantee the safety of RC deep beams with openings in real-world applications, the study's examination of various strengthening techniques aids in the identification of feasible solutions to restore strength, stiffness, and durability.

1.4. Novelty of Work

In order to provide engineers with a comprehensive guide for handling this specific problem in modern building techniques, the review attempts to gather the most recent research on these external strengthening techniques, with resource efficiency, sustainability, and structural safety becoming more important. This work makes more contributions to the development of civil engineering solutions for RC deep beams with apertures. Since no existing literature review compiles various external strengthening techniques into a single study, hence this review is more valuable.

2. Historical Studies on RC Deep Beam's Performance

With Perforation, Yang et al. [24] investigated the RC deep beam's structural behaviour that features web holes. To conduct their investigation, ten deep beams of RC with slots were tested until they failed. The ratio of shear span-to-depth and the opening's location and size were the main factors under investigation. The result showed a considerable decline in the load-carrying ability of continuous deep beams when the shear span zone disturbed by the web increased in size of openings. Similar patterns were observed in deep beams with web holes under simply supported conditions. Moreover, regardless of the shear span-to-depth ratio, two distinct failure mechanisms were identified based on the placement and size of the web apertures.

Beams with apertures outside the shear span, the area proportion of openings and shear span impacted the transition between failure modes. For additional insights into this topic, investigations looking at the effects on deep beam behaviour with an opening in the web, such as those conducted by Ata et al., may be useful. They provide a thorough examination of failure modes and the significance of opening placements. In this study on the deep beam's strength cast with reinforcement concrete along with openings provided in its web, Kubik et al. [23] found that photo elastic models are effective in identifying stress concentrations that may arise during concrete or steel prototype beam testing. A deep beam of reinforced concrete having a big square opening disrupted the load path, creating a noticeable deformed fringe pattern. Notable stress concentrations were seen at the corners of the hole and beneath the load point. The finding revealed that significant internal cracking resulted from the development of large tensile stress intensity zones in addition to large stress concentration locations.

Hu et al. experimented to assess the shear strength capacity of deep beams that have holes in the web. They tested three specimens of deep beams provided with openings alongside one standard beam, all of which had compressive strength ranging from 35 to 44 MPa. A two-point symmetric loading technique was used to load the beams until they failed.

The specimens had measurements of 2000 mm in depth, 4000 mm in total length, and 220 mm in web thickness. Three beams featured with 500 x 550 mm web openings located within their shear span. The shear span for the beam with openings was maintained between 500 and 900 mm. It was observed that if an opening in the web interferes with the load route connecting the point of load and support, it can greatly diminish a huge deep beam's ultimate strength, as shown in Figure 1. The patterns of crack observed indicated a strut-and-tie model in this huge deep beam with holes. Figure 2 illustrates the usual cracking patterns found in the deep beam.

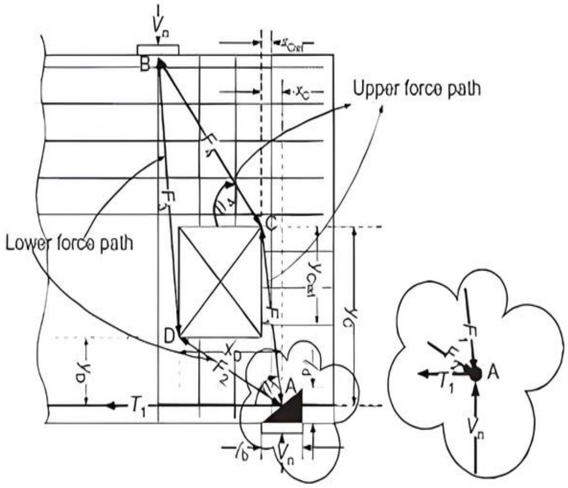

Fig. 1 Pathways of load for opening in web of deep beam [23]

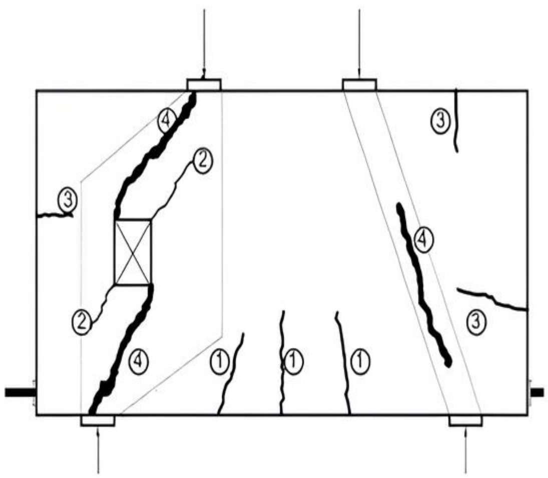

Fig. 2 Common cracks in the deep beam [23]

Holes in the web of RC deep beams can decrease the structural ability of the beam and potentially change the failure mechanism. The decline of the concrete area in critical shear zones notably weakens the beam's shear strength, raising important problems with serviceability.

Effective strategies like external strengthening techniques must be implemented to mitigate the strength loss associated with these openings to restore and enhance the beam's capacity.

In this work last 10 years, literature has been studied and focus on the strengthening techniques must be studied and focused on the strengthening techniques used to enhance the strength of the deep beam, which is reduced due to the opening's shape, size, and location.

3. External Strengthening Techniques

3.1. Fiber-Reinforced Polymer of Carbon

Rahim et al. [7], an experimental investigation, looked into the shear zone structural performance of deep beams having web openings strengthening using FRP materials that are externally bonded. The researcher analyzed several structural aspects, including reinforcement factors, failure modes, behaviour of load-deflection, stress concentrations, and cracking patterns.

The experiment involved testing nine CFRP-strengthened RC deep beams, as shown in Figure 3, and one control beam without any opening under static four-point loading until breakdown. Specimen details are given in Table 1. The load-deflection graph of all groups is given in Figures 4, 5, and 6. The outcome showed that larger openings could reduce shear strength by up to 30%.

Consequently, the capacity of load-carrying decreased with the opening size, although raising the quantity of CFRP layers could improve this capacity. In summary, the RC deep beam's shear performance was improved by 10% to 40% by wrapping the CFRP layer.

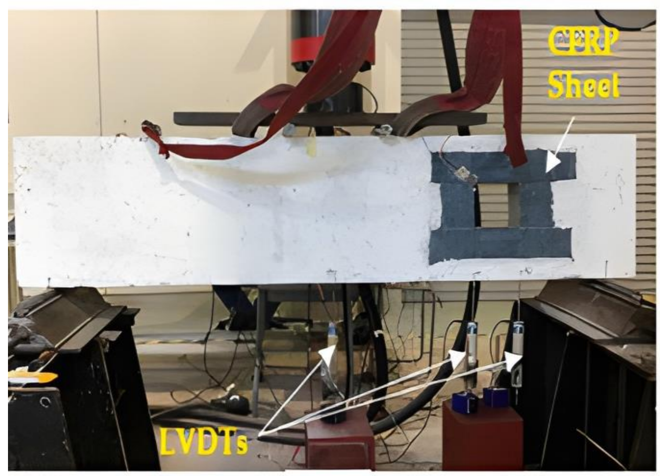

Fig. 3 Beam strengthened with CFRP [7]

Table 1. Details of specimens [7]

Beam's ID	Openings Size (mm)		Layers of CFRP
	Width	Height	
Control Beam	0	0	0
B3a	250	250	1
B3b	250	250	2
B3c	250	250	3
B2a	200	200	1
B2b	200	200	2
B2c	200	200	3
B1a	150	150	1
B1b	150	150	2
B1c	150	150	3

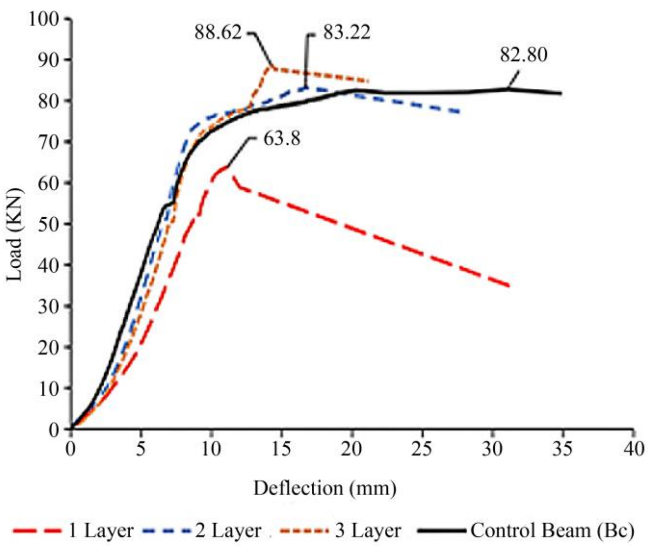

Fig. 4 Load-deflection diagram of group 1 [7]

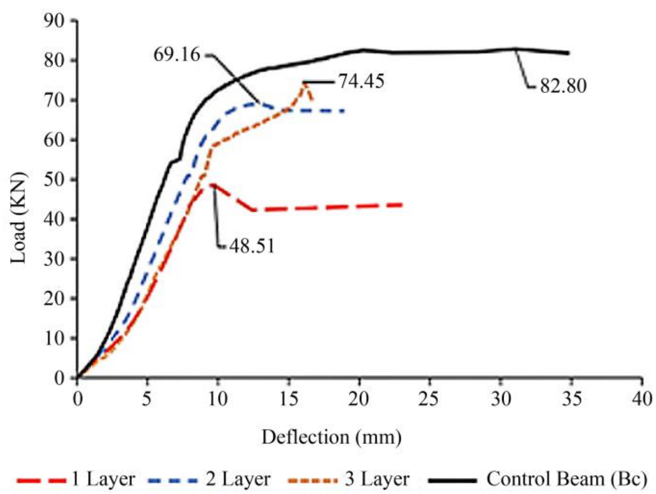

Fig. 5 Load-deflection diagram of group 2 [7]

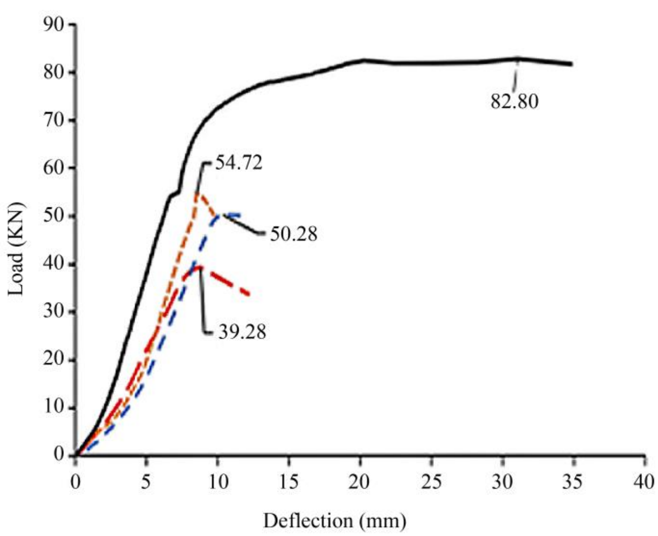

Fig. 6 Load-deflection diagram of group 3 [7]

3.2. Galvanized Flat and Corrugated Steel Sheets

Hamoda et al. [4] examined the performance of deep beams by providing openings reinforced by flat sheets of galvanized corrugated steel. The practical study involved ten deep beam specimens, and every measurement was 750 mm in length, 400 mm in depth, and 120 mm in thickness, with various opening configurations, as given in Table 2. These openings were reinforced by wrapping them with GFSS and GCSS, which are shown in Figures 7 and 8. Compared to the control beam, the results indicated that the beams strengthened using galvanized steel sheets had improved ultimate load, energy absorption capability, and initial stiffness. Additionally, the results showed that as plate thickness increased, shear strength also increased. The load-deflection behaviour of all beams strengthened with GFSS and GCSS are shown in Figures 9 and 10, respectively. For practical purposes, galvanized steel sheets used to strengthen deep beams be advised to have an opening ratio of 0.33. The strengthening techniques employing GFSS and GCSS increased the reinforced beam's maximum load-bearing capacity over the unreinforced normal beam by 58 % and 60 %, respectively.

Table 2. Details of specimens [4]

Group	Beam's ID	Opening Condition	Size (mm)	Strengthening Type
Control	B0	-	-	-
G1	B-GCSS	-	-	-
	B-GCSS-C1	Circular	75	Corrugated sheet
	B-GCSS-C1	Circular	100	Corrugated sheet
	B-GCSS-R1	Square	75	Corrugated sheet
	B-GCSS-R2	Square	100	Corrugated sheet
G2	B-GFSS	-	-	-
	B-GFSS-C1	Circular	75	Flat Sheet
	B-GFSS-C2	Circular	100	Flat Sheet
	B-GFSS-R1	Square	75	Flat Sheet
	B-GFSS-R2	Square	100	Flat Sheet

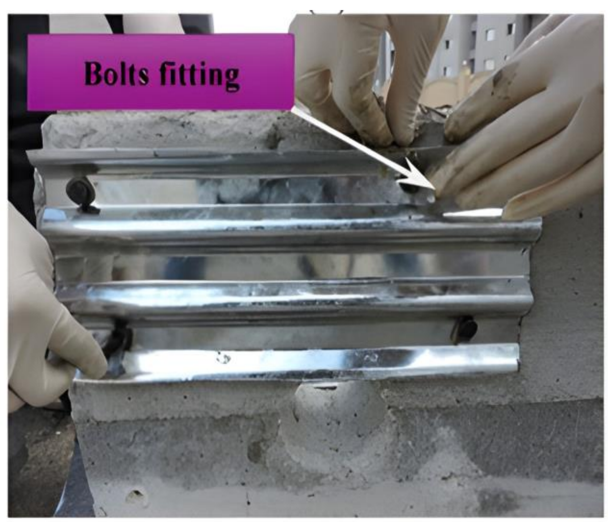

Fig. 7 Opening strengthened with GCSS [4]

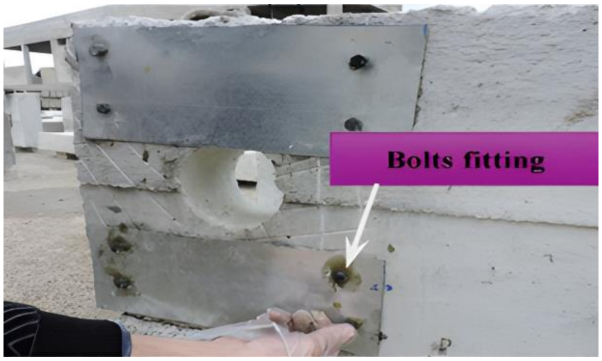

Fig. 8 Opening strengthened with flat steel sheet [4]

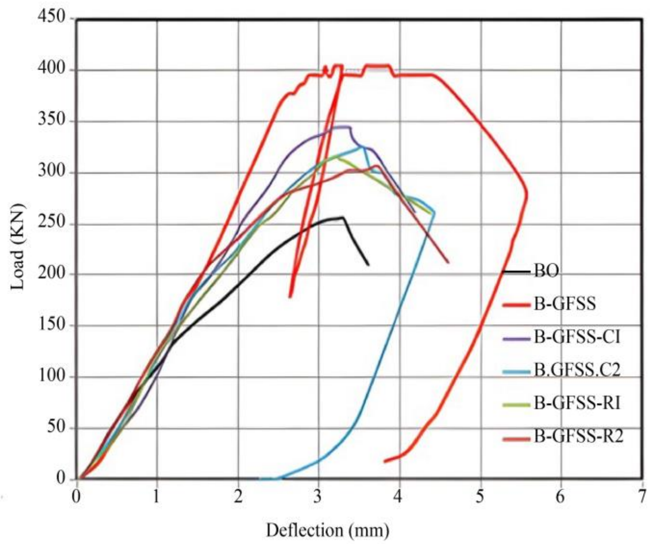

Fig. 9 Load-deflection responses for all GFSS strengthened deep beams [4]

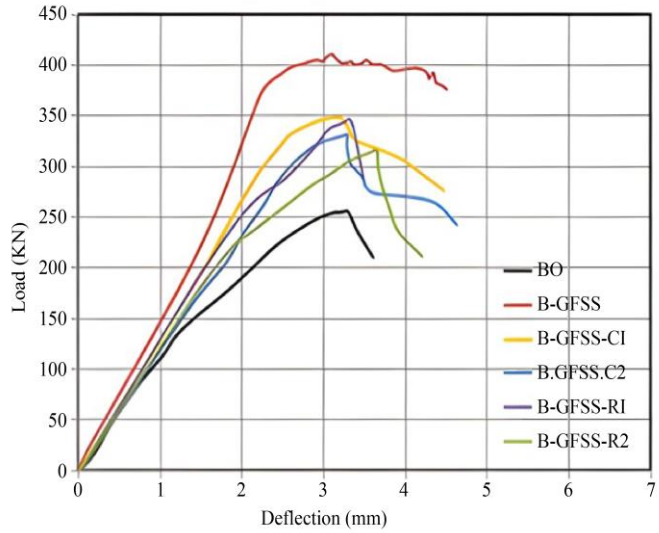

Fig. 10 Load-deflection responses for all GCSS strengthened deep beams [4]

3.3. FRP Lamination Compared with Finite Element Modelling (FEM)

Hawlileh et al. [6] explored FEM, which is nonlinear for deep beams cast by RC with holes that were reinforced using joined composite externally. The nonlinear finite element models in 3D were designed to reflect the nonlinear behaviour of materials by incorporating actual material constitutive laws.

Table 3 contains information about the specimens. In this model, the link element represented the steel reinforcement, the concrete was represented by solid elements, and the CFRP was applied by multi-layer shell elements.

Table 3. Details of specimens [6]

ID of Beam	Location of Opening	Externally Strengthened by CFRP	FE Model	Opening Size (mm)
FS250C	Shear Span Centre	Yes	FE FS250C	250 x 250
NS250C	Shear Span Centre	No	FE NS250C	250 x 250
FS200C	Shear Span Centre	Yes	FE FS200C	200 x 200
NS200C	Shear Span Centre	No	FE NS200C	200 x 200
NS250T	Shear span top side near support	No	FE NS250T	250 x 250
NS200T	Shear span top side near support	No	FE NS200T	200 x 200
FS250T	Shear span top side near support	Yes	FE FS250T	250 x 250
NS200B	Shear span bottom side near loading point	No	FE NS200B	200 x 200
NS150B	Shear span bottom close to the loading point	No	FENS 150B	150 x 150
FS250B	Shear span bottom close to the loading point	Yes	FEFS 250B	250 x 250
N250B	Shear span bottom close to the loading point	No	FENS 250B	250 x 250

Moreover, specific interface features were incorporated to simulate the binding interactions between the CFRP and concrete composites. The model of deem beam with an opening in FEM software is shown in Figure 11. The comparison of the result obtained by finite element analysis and the experimental data from other studies showed that the models for computation successfully replicated the structural responses of both CFRP-reinforced and unreinforced deep beams along with openings. The finite element model's crack patterns closely matched the experimental observations. The estimated deflection capacity had an inaccuracy of only 14% margin, while the expected failure loads had a 3.2% error margin. Overall, the finite element analysis confirmed the experimental results, demonstrating that CFRP shear strengthening greatly improves the beam's load carrying.

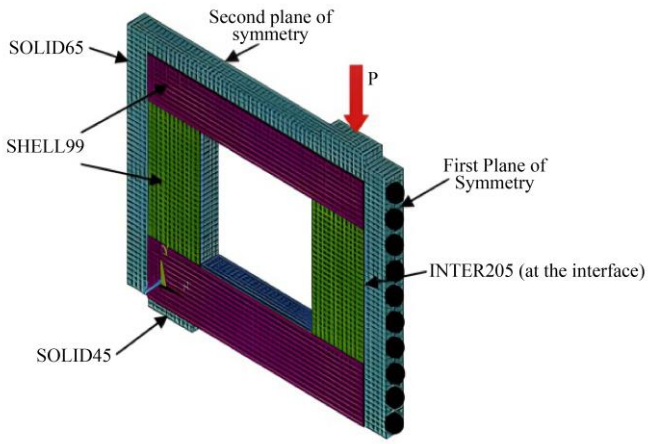

Fig. 11 Finite Element Model of deep beam [6]

3.4. Glass Fiber Reinforced Polymer (GFRP)

Additionally, Kumar [25] conducted experimental studies to evaluate the effectiveness of GFRP in reinforcing deep beams with the provision of openings. The research involved five deep beams with the provision of openings assessed with three-point loading conditions without shear reinforcement. A key focus of this investigation was the configuration of the GFRP lamination.

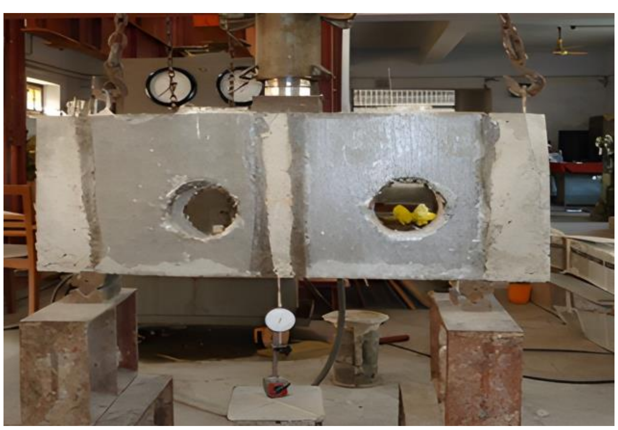

Fig. 12 Beam wrapped with GFRP [25]

Each beam's cross-section was 150 by 640 mm with 1200 mm overall length, with circular shape openings symmetrically positioned within every shear span at the midpoint. Applying GFRP that has been externally bonded around the openings, as shown in Figure 12, led to a notable increase in the beam's load-carrying capacity, ranging from 68% to 125%. The findings revealed that configurations employing four layers of close-together GFRP in U-wrap and four layers of widely spaced GFRP in full wrap outperformed those with two layers of U-wrap and two layers of full-wrap arrangements.

3.5. Metal Plates

Amin et al. [5] studied the use of metal plates to increase the strength of reinforced concrete deep beams with openings. To study the impact of different metal plate orientations on the load-carrying capacity and the structural behaviour of the deep beams, Abaqus the FEM software is used. In addition to four distinct scenarios of adding a load of 5000 kN following the validation of the original beam against experimental results, this work provides a thorough model calibration and sensitivity analysis of the original model against experimental results. After validating the initial beam against experimental results, this work contains four distinct examples of applying a load of 5000 kN and a thorough model calibration and sensitivity analysis of the original model against experimental results. The four cases are given and also shown in Figure 13.

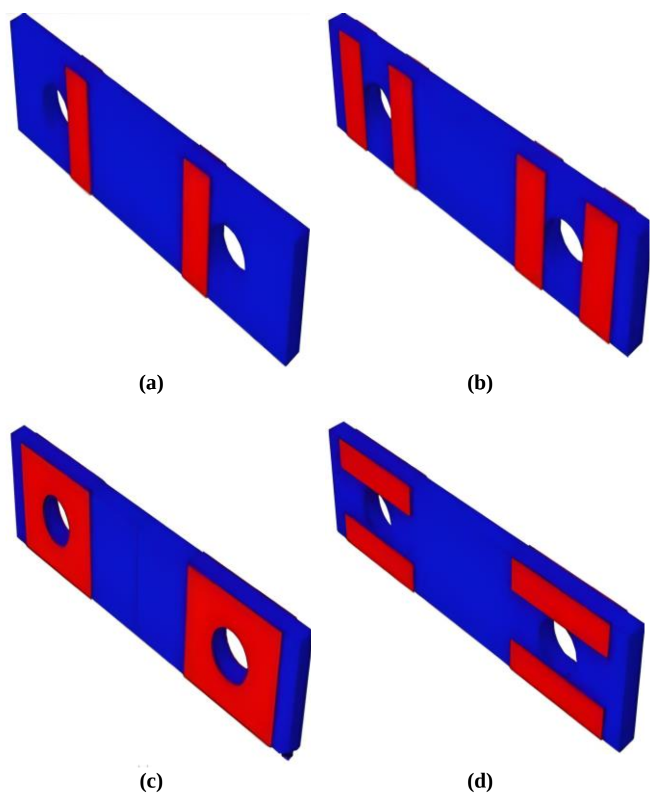

Fig. 13 Metal plate orientation (a) Case I, (b) Case II, (c) Case III, and (d) Case IV [5]

Case 1 - The metal plate is positioned between the deep beam's two circular apertures on each side. The metal plate is 200 mm in length and 600 mm in height.

Case 2 - On the right and left sides of each opening in deep beam.

Case 3 - The deep beam's two circular openings are directly covered by the metal plate, which measures 670 mm in length and 600 mm in height, omitting the circular openings themselves.

Case 4 - On the sides of the deep beam, the metal plate is positioned below and above the circular openings. The height and length of the metal plate are 165 mm and 670 mm, respectively.

According to the study, Case 3 performs better at reducing deflection since it has the largest load-bearing capacity and the least amount of deflection, as shown in Figure 14. However, because the metal plates utilized in the Case 3 design are expensive, Case 4 is a more cost-effective option.

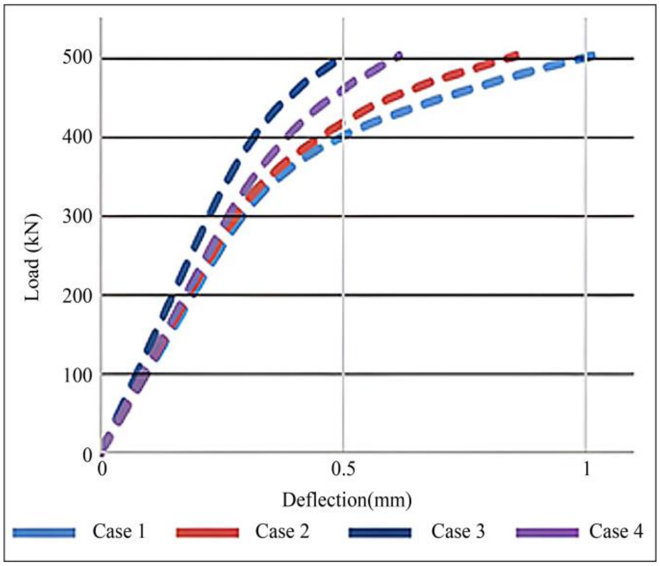

Fig. 14 Load-deflection curve comparison of all four cases [5]

3.6. CFRP with Ultra High-Performance Fiber Reinforced Concrete (UHPFRC)

Abadel et al. investigated how well shear stirrups and carbon fiber reinforced polymer reinforcing might increase the shear strength of the deep beam. This group of two deep beam specimens each, a total of six specimens measuring 150 x 300 x 1000 mm with 750 mm as an effective span, were cast. The initial group's beam was made of regular concrete. UHPFRC was used to prepare another group's beams. In the third group, the UHPFRC deep beam was strengthened with carbon fiber-reinforced polymer strips. Each group had two beams: one without stirrups and another without stirrups with four-point loading applied to every deep beam until it failed. The testing results showed that shear stirrups significantly improved the deep beam's ultimate load, shear strength, and deformation capacity. Compared to regular concrete deep beams, the shear strength of the deep beam was greatly increased by using the UHPFRC mix. The strengthening plan that was put into place effectively increased the deep beam's shear strength and deformation capacity. Figures 15 and 16 show the peak load taken by all specimens and their deflection under loading, respectively. The reinforced UHPFRC deep beam showed a moderate increase in shear strength. However, the energy ductility indices and displacement increased by 185 % and 49% respectively. A significant increase in the deformation capacity was noted.

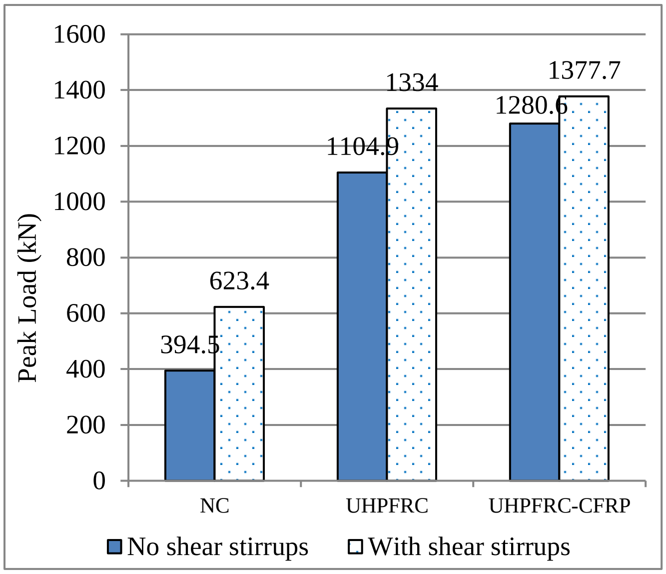

Fig. 15 Peak load of all specimens [22]

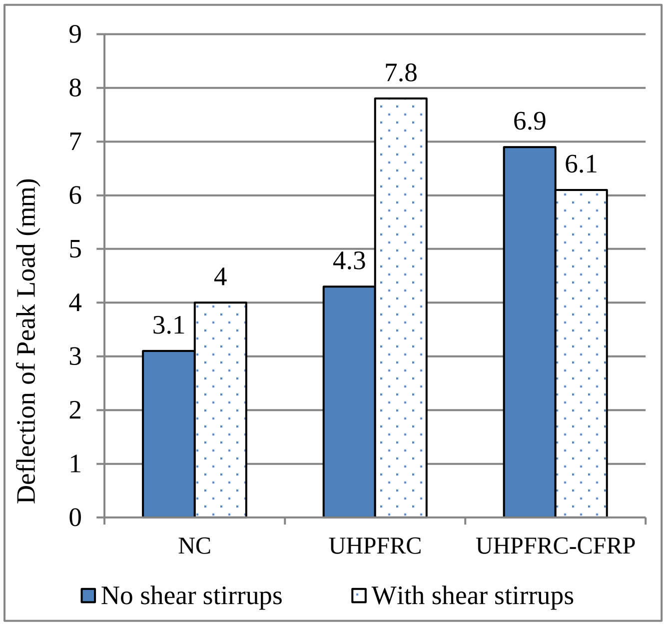

Fig. 16 Corresponding deflection of peak load [22]

3.7. Summary

Table 4. An overview of RC deep beam with apertures that are externally strengthened

Name of Author	Opening			Material Used for Strengthening	Strengthening System	Strength Regain
	Shape	Location	Size (mm)			
Rahim et al. [7]	Square	One opening in the middle of a single shear span.	150 x 150 200 x 200 250 x 250	CFRP	Single-layer, Double-layer, triple-layer.	10-40%
Hamoda et al. [4]	Circular and Square	One opening in the middle of a single shear span.	75,100 radius and 75 x 75, 100 x 100	GFSS and GCSS	One sheet is at the top, and another is at the bottom of the opening.	58% by GFSS and 60 % by GCSS
Hawileh et al. [6]	Square	Two apertures (one for each shear span).	200x200 250x250	CFRP	Both vertically and horizontally surrounding the aperture, U-wrap and full wrap.	Good agreement with the result of FEM
Amin et al. [5]	Circular	Two apertures (one for each shear span).	270	Metal plate	Plates were provided around the openings.	Good agreement with the result of FEM
Kumar [25]	Circular	Two apertures (one for each shear span).	-	GFRP	Two-layer full wrap GFRP, four-layer complete wrap, four-layer U wrap, and two-layer U wrap (largely and closely spaced).	68 -125%

4. Conclusion

Openings in RC deep beams significantly affect their structural performance by reducing their shear strength, changing failure mechanism, and increasing stress concentrations and deflections. This review has examined various external strengthening techniques to restore and enhance the load-carrying capacity of deep beams with openings.

Additionally, numerical and experimental studies demonstrated that Finite Element Analysis is a reliable tool for predicting the structural behaviour of deep beams with openings. The results showed that externally bonded CFRP composites significantly improved the load-bearing capacity and closely matched experimental findings with minimal error margins. Moreover, metal plates have been explored as an alternative reinforcement method, with certain configurations showing substantial performance improvements, although cost considerations must be accounted for when selecting the optimal design. The review also highlighted the application of UHPFRC with CFRP, further enhancing both shear strength and deformation capacity.

4.1. Implications for Engineering Practices and Standards

This paper emphasizes the useful implications for engineering design and construction standards in addition to providing an overview of recent developments. The results show that the safety and durability of RC deep beams with openings may be improved by including external strengthening techniques in design codes. Future studies should also build prediction models for beam behavior under various loading scenarios, optimize reinforcement procedures, and investigate hybrid strengthening materials. Deep beam structures in contemporary infrastructure will be more resilient thanks to these findings, which will also help to improve building standards.

4.2. Ethical Consideration

This review compiles with ethical research standards by ensuring data interpretation is accurate, reliable, and transparent. Every source used in this research is correctly cited to protect original authorship. No purposeful bias or data falsification occurred during the objective literature selection process.

Acknowledgements

The authors would like to acknowledge and sincerely thank the organizing committee of the International Conference on Computer-Aided Modelling for the Sustainable Development of Smart Cities (CAMSSC), sponsored by the Anusandhan National Research Foundation (ANRF), held at the Department of Civil Engineering, North Eastern Regional Institute of Science and Technology (NERIST), Nirjuli, Arunachal Pradesh, India, during November 27–30, 2024, for allowing us to present the paper and sponsoring the paper for publication.

References

[1] Hong Guan, “Effect of Sizes and Positions of Web Openings on Strut-and-Tie Models of Deep Beams,” *Advances in Structural Engineering*, vol. 8, no. 1, pp. 69-84, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[2] Somsak Swaddiwudhipong, and Nandivarann E. Shanmugam, “Fiber-Reinforced Concrete Deep Beams with Openings,” *Journal of Structural Engineering*, vol. 111, no. 8, 1679-1690, 1985. [CrossRef] [Google Scholar] [Publisher Link]

[3] A.F. Ashour, “Shear Capacity of Reinforced Concrete Deep Beams,” *Journal of Structural Engineering*, vol. 126, no. 9, pp. 1045-1052, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[4] Ahmed Hamoda et al., “Experimental and Numerical Analysis of Deep Beams with Openings Strengthened with Galvanized Corrugated and Flat Steel Sheets,” *Case Studies in Construction Materials*, vol. 21, pp. 1-22, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Fayiz Amin et al., “Strengthening of Reinforced Concrete Deep Beams with Large Openings Using Metal Plates,” *Emirati Journal of Civil Engineering and Applications*, vol. 1, no. 1, pp. 31-44, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[6] Rami A. Hawileh, Tamer A. EI Maaddawy, and Mohannad Z. Naser, “Nonlinear Finite Element Modeling of Concrete Deep Beams with Openings Strengthened with Externally-Bonded Composites,” *Materials & Design*, vol. 42, pp. 378-387, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[7] Nurul Izzati Rahim et al., “Strengthening the Structural Behavior of Web Openings in RC Deep Beam Using CFRP,” *Materials*, vol. 13, no. 12, pp. 1-21, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Wen-Yao Lu et al., “Shear Strength of Reinforced Concrete Deep Beams with Web Openings,” *Journal of the Chinese Institute of Engineers*, vol. 43, no. 7, pp. 694-705, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] O.E. Hu, and K.H. Tan, “Large Reinforced-Concrete Deep Beams with Web Openings: Test and Strut-and-Tie Results,” *Magazine of Concrete Research*, vol. 59, no. 6, pp. 423-434, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[10] Adriano Silva de Carvalho et al., “Moment Gradient Factor for Steel I-Beams with Sinusoidal Web Openings,” *Journal of Constructional Steel Research*, vol. 202, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Samadhan G. Morkhade, Laxmikant M. Gupta, and Carlos Humberto Martins, “Effect of Web Post Width on Strength Capacity of Steel Beams with Web Openings: Experimental and Analytical Investigation,” *Practice Periodical on Structural Design and Construction*, vol. 27, no. 2, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Gamil M.S. Abdullah et al., “The Effect of Openings on the Performance of Self-Compacting Concrete with Volcanic Pumice Powder and Different Steel Fibers,” *Case Studies in Construction Materials*, vol. 17, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Khattab Saleem Abdul-Razzaq, and Mais Malallah Abdul-Kareem, “Innovative use of Steel Plates to Strengthen Flange Openings in Reinforced Concrete T-Beams,” *Structures*, vol. 16, pp. 269-287, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[14] Moatez Alhassan, and Zahraa Khudhair, “Strengthening Reinforced Concrete Deep Beams with Web Openings Using CFRP, Steel Plates, and Skin Reinforcement,” *Journal of Structural Design and Construction Practice*, vol. 30, no. 1, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[15] Tamer El Maaddawy, and Sayed Sherif, “FRP Composites for Shear Strengthening of Reinforced Concrete Deep Beams with Openings,” *Composite Structures*, vol. 89, no. 1, pp. 60-69, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[16] N.E. Shanmugam, and S. Swaddiwudhipong, “Strength of Fibre Reinforced Concrete Deep Beams Containing Openings,” *International Journal of Cement Composites and Lightweight Concrete*, vol. 10, no. 1, pp. 53-60 1988. [CrossRef] [Google Scholar] [Publisher Link]

[17] F. El Ame, J.N. Mwero, and C.K. Kabubo, “Openings Effect on the Performance of Reinforced Concrete Beams Loaded in Bending and Shear,” *Applied Science Research*, vol. 10, no. 2, pp. 5352-5360, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ahmed M. Sayed, “Numerical Study using FE Simulation on Rectangular RC Beams with Vertical Circular Web Openings in the Shear Zones,” *Engineering Structures*, vol. 198, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ahmed A. Elansary e al., “Shear Behavior of Reinforced Concrete Beams with Web Opening Near Supports,” *Structures*, vol. 37, pp. 1033-1041, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Meshal S. Al-Enezi, Ahmed M. Yousef, and Ahmed M. Tahwia, “Shear Capacity of UHPFRC Deep Beams with Web Openings,” *Case Studies in Construction Materials*, vol. 18, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] Mona Saleh, Mohammad AlHamaydeh, and Mohamed Zakaria, “Finite Element Analysis of Reinforced Concrete Deep Beams with Square Web Openings using Damage Plasticity Model,” *Engineering Structures*, vol. 278, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] Aref Abadel et al., “Experimental Study of Shear Behavior of CFRP Strengthened Ultra-High-Performance Fiber-Reinforced Concrete Deep Beams,” *Case Studies in Construction Materials*, vol. 16, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] L.A. Kubik, and J.E. Gibson, “Discussion. Predicting the Strength of Reinforced Concrete Deep Beams with Web Openings,” *Proceedings of the Institution of Civil Engineers*, vol. 71, no. 2, pp. 615-616, 1981. [CrossRef] [Google Scholar] [Publisher Link]

[24] K.H. Yang, and A.F. Ashour, “Structural Behaviour of Reinforced-Concrete Continuous Deep Beams with Web Openings,” *Magazine of Concrete Research*, vol. 59, no. 10, pp. 699-711, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[25] G. Hemanth Kumar, "*Experimental and Numerical Studies on Behaviour of FRP-Strengthened Deep Beams with Openings*," Thesis (MTech), Department of Civil Engineering, National Institute of Technology, Rourkela, pp. 1-74, 2012. [Google Scholar] [Publisher Link]

[26] ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-19)*, American Concrete Institute, pp.1-623, 2019. [Google Scholar] [Publisher Link]

[27] "*Design of concrete structures*," Canadian Standards Association, Report, pp. 1-240, 2004. [Google Scholar]

[28] "*Indian Standard: Plain and Reinforced Concrete- Code of Practice*," Code of Practice: I.S. 456, Report, Bureau of Indian Standards, New Delhi, pp.1-107, 2000. [Google Scholar] [Publisher Link]

[29] "*Eurocode 2: Design of Concrete Structures, Part I: General Rules and Rules for Buildings*, European Committee for Standardization, ENV 1992-1-1, pp. 1-225, 1992. [Google Scholar] [Publisher Link]