Review on experimental study on shear strengthening of RC Beams with post formed circular opening using CFRP

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***Abstract*—The presence of post-formed circular openings in reinforced concrete (RC) beams, often introduced to accommodate utility services, significantly alters the stress distribution and reduces shear capacity. This structural vulnerability has been widely documented, with researchers reporting increased crack propagation and premature shear failure in beams with openings. Traditional strengthening methods, such as steel jacketing and concrete encasement, have shown limited effectiveness due to added weight, corrosion issues, and construction complexity. In recent decades, Fiber Reinforced Polymer (FRP) systems have emerged as efficient alternatives, offering high strength-to-weight ratios and durability. Among these, Carbon Fiber Reinforced Polymer (CFRP) have demonstrated superior performance in enhancing shear resistance and restoring load capacity. Experimental studies highlight the influence of parameters such as opening size and location, fiber orientation, and bonding techniques on strengthening efficiency. Comparative investigations consistently show CFRP outperforming conventional methods, though challenges remain regarding installation quality and long-term performance. The reviewed literature underscores the need for further experimental evaluation of RC beams with post-formed circular openings strengthened using CFRP, particularly to address gaps in understanding failure modes and service behavior.**

***Index Terms*—Bond Behavior, CFRP, Post-formed circular openings, RC beams, Strengthening.**

I. INTRODUCTION

Reinforced concrete (RC) beams are fundamental structural elements widely used in modern construction. However, the incorporation of post-formed circular openings in beams—often required for service ducts, mechanical systems, or architectural purposes—can significantly weaken their shear capacity and overall structural performance. This reduction in strength has prompted extensive research into effective strengthening techniques. Among these, the use of externally bonded Carbon Fiber Reinforced Polymer (CFRP) has emerged as a promising solution due to their high tensile strength, lightweight nature, and resistance to corrosion.

Previous studies have highlighted that openings in RC beams alter stress distribution, leading to stress concentrations and potential shear failure. Researchers have investigated various strengthening methods, including steel plates, FRP laminates, and hybrid systems, with CFRP showing superior performance in restoring shear capacity and enhancing ductility. Literature also emphasizes the importance of parameters such as the size and location of openings, orientation of CFRP fibers, and bonding techniques, all of which influence the effectiveness of strengthening. By synthesizing these findings, the present study builds upon existing knowledge to experimentally evaluate the shear behavior of RC beams with circular openings strengthened using CFRP.

II. LITERATURE REVIEW

This section discusses previous studies on reinforced concrete (RC) beams with web openings and their strengthening techniques. Various approaches adopted by researchers to restore strength and stiffness lost due to openings are briefly reviewed. Special emphasis is placed on studies involving Carbon Fiber Reinforced Polymer (CFRP) laminates, both with and without anchorage systems. The effectiveness of CFRP in enhancing load-carrying capacity, controlling crack propagation, and improving overall structural performance around the openings is highlighted. The review of existing literature helps identify key findings, common strengthening strategies, and limitations, while also pointing out areas where further research is required, particularly in optimizing laminate configurations and anchorage methods for beams with openings.

[1] Mohamed Ghalla et al. (2025) conducted an experimental and numerical investigation on restoring the shear capacity of reinforced concrete (RC) beams with circular web openings using three strengthening techniques: externally bonded aluminum sheets (EBR-AS), stainless steel sheets (EBR-SSS), and near-surface mounted GFRP bars (NSM-GFRP). The methodology involved testing nine simply supported RC beam specimens with circular openings under three-point loading to study parameters such as crack initiation, ultimate load, stiffness, and energy absorption. Additionally, finite element modelling using ABAQUS was performed and validated with experimental results. The results indicated that strengthening significantly improved shear performance, where the combination of two parallel and two perpendicular stainless-steel sheets with anchorage showed the highest efficiency, increasing cracking load by 59%, ultimate load by 65%, stiffness by 116%, and energy absorption by 265% compared to the control beam. Aluminum sheets also provided considerable improvement, while NSM-GFRP bars showed comparatively lower enhancement. The study concluded that externally bonded stainless-steel sheets with proper anchorage are the most effective technique for strengthening RC beams with web openings, offering superior load capacity, durability, and structural performance.

[2] Bashir H. Osman et al. (2017) studied the shear behavior of reinforced concrete beams with circular web openings without additional shear reinforcement using both experimental and finite element methods. Four beams were tested under two-point loading, and numerical analysis was performed using ANSYS software considering parameters such as opening size, location, and shear span-to-depth ratio. The results indicated that openings significantly reduce shear strength, stiffness, and load capacity, with nearly 30% reduction observed compared to solid beams. Beams with openings in high shear regions failed earlier due to stress concentration and crack propagation. The finite element results showed good agreement with experimental findings. The study concluded that openings negatively affect beam performance, and the proposed analytical model can effectively predict shear strength, reducing the need for extensive experimental work.

[3] Y.O. Özkılıç et al. (2022) performed a numerical study using ABAQUS software to evaluate the behavior of RC beams with circular openings strengthened using CFRP composites. The methodology involved developing 95 finite element models considering parameters such as opening size, location, number of CFRP layers, and wrapping configuration. The results revealed that an increase in opening size leads to a reduction in load capacity, whereas proper CFRP strengthening significantly improves strength, stiffness, and ductility, with some configurations increasing load capacity up to 69%. The study concluded that CFRP strengthening is highly effective, and fully wrapped configurations provide better structural performance compared to partial wrapping.

[4] Huda Saad Abed et al. (2023) conducted an experimental and analytical investigation on the effect of web openings on reinforced concrete (RC) deep beams and their strengthening using CFRP laminates. The methodology involved testing 13 RC deep beam specimens with different opening shapes (circular and square), sizes, and locations within the shear span under four-point loading. Some beams were

strengthened and repaired using CFRP laminates with different orientations (0°, 45°, and 90°), and analytical evaluation was carried out using the strut-and-tie model. The results showed that the presence of openings significantly reduced shear strength by about 22% to 74%, depending on size, shape, and location, while stiffness and toughness also decreased considerably. However, strengthening with CFRP laminates improved shear strength by 17% to 48%, stiffness by 0.7% to 17%, and toughness by 4% to 20%, with the 45° orientation showing the best performance. Additionally, CFRP was able to restore nearly 100% of the load-carrying capacity of damaged beams. The analytical results closely matched experimental findings, confirming the reliability of the adopted model. The study concluded that web opening adversely affects the structural behavior of RC deep beams, but CFRP laminates are an effective solution for strengthening and rehabilitation, significantly improving strength, stiffness, and overall performance.

[5] Aykac et al. (2013) investigated the flexural behavior of reinforced concrete (RC) beams with multiple square and circular web openings. In their experimental program, nine rectangular beams (150 × 400 mm section, 3900 mm span) were tested under six-point bending to simulate distributed loading. The parameters considered included opening geometry (square vs. circular), reinforcement ratio (light, moderate, heavy), and the presence of diagonal reinforcement around openings. The results showed that beams with square openings were more prone to Vierendeel action, especially in moderately and heavily reinforced specimens, where plastic mechanisms with four hinges developed in the chords, leading to shear failure of posts. In contrast, beams with circular openings exhibited tension-controlled flexural failure without significant Vierendeel action, largely due to reduced stress concentrations at curved edges and the effectiveness of diagonal reinforcement in controlling cracks. The study concluded that circular openings, when combined with proper diagonal reinforcement, provide more ductile flexural behavior and maintain solid beam action, whereas square openings significantly reduce rigidity and ductility, making reinforcement detailing critical to prevent premature failure.

[6] Aksoylu et al. (2020) carried out an experimental study on shear-deficient reinforced concrete beams with circular web openings, strengthened using carbon fiber reinforced polymer (CFRP) composites. Eleven half-scale specimens were tested under two-point static loading, with hole diameter-to-beam height ratios (D/H) of 0.30, 0.44, and 0.64. Two CFRP strengthening configurations were applied: vertical sheet wrappings near openings (CFRP-1) and combined vertical plus full wrapping around openings (CFRP-2). The results showed that beams with D/H = 0.30 exhibited ductile behavior and increased load capacity, while larger openings (D/H = 0.44 and 0.64) caused significant reductions in shear strength and brittle failures. CFRP strengthening improved both load capacity and ductility, with CFRP-2 performing better than CFRP-1 by preventing premature shear damage and achieving bending-type failure in some cases. However, no CFRP configuration was effective for beams with very large openings (D/H = 0.64), where shear failure dominated. The study concluded that CFRP composites are effective for strengthening RC beams with moderate-sized circular openings, but the D/H ratio should be limited to 0.30 in practice to ensure ductile performance and reliable strengthening outcomes.

[7] Shoeib et al. (2017) investigated the reduction of shear strength in reinforced concrete (RC) beams due to introduced openings and the effectiveness of strengthening techniques. Their experimental program involved fifteen rectangular beams (150 × 300 × 1650 mm), divided into groups based on opening size (Ø75 mm and Ø150 mm), shape (circular, square, rectangular), timing of opening creation (before casting, after casting, and under load), and strengthening method (external CFRP sheets and internal discrete steel fibers). The results showed that introducing openings significantly reduced stiffness, cracking load, and ultimate load capacity, with larger openings (Ø150 mm) causing up to 67% reduction compared to control beams. Openings created under load produced more brittle failures due to additional cracks around the opening zone. Strengthening with CFRP sheets reduced crack widths and improved ductility, while steel fibers enhanced ductility indices (up to 6.35) but had limited effect on ultimate load. The study concluded that vertical stirrups adjacent to openings resist 35–65% of shear forces and must be

considered in design, while CFRP and steel fibers can partially restore strength and ductility. However, strengthening efficiency depends strongly on opening size, shape, and timing of introduction, with smaller circular openings showing more controlled crack behavior than square or rectangular ones.

[8] Amiri et al. (2011) reviewed and analyzed the effects of web openings on reinforced concrete beams, including precast, prestressed, T-beams, and deep beams. Their study synthesized findings from earlier experimental and analytical works to evaluate the influence of opening size, shape, and location on beam strength and behavior. Using finite element simulations and comparisons with experimental data, they examined rectangular and circular openings of varying diameters and positions. The results indicated that small openings (less than 0.25–0.33 of beam depth) had minimal impact on ultimate capacity, while larger openings significantly reduced stiffness, increased deflections, and promoted Vierendeel action. For continuous beams, openings caused redistribution of internal forces and moments, leading to early cracking and hinge formation at opening corners. The study highlighted that deeper or longer openings reduced collapse loads by up to 25–75%, depending on geometry, and altered failure modes from flexural to shear. Strengthening with FRP sheets or steel plates was shown to restore capacity for smaller openings but was less effective for larger ones. The authors concluded that proper reinforcement detailing around openings—such as diagonal bars, stirrups, and external strengthening—was essential to maintain ductility and prevent premature failure, while openings exceeding 0.48D should be avoided to ensure safe performance.

[9] Mondal et al. (2011) investigated the strengthening and rehabilitation of reinforced concrete (RC) beams with openings using glass fiber reinforced polymer (GFRP) sheets. Their experimental program consisted of ten beams: one solid reference beam and nine beams with rectangular openings of varying sizes (100 × 100 mm, 200 × 100 mm, and 300 × 100 mm) placed in the shear zone. Each group included an unstrengthened beam with opening, a beam strengthened with GFRP wrapping before loading, and a rehabilitated beam retrofitted with GFRP after cracking. The results showed that beams with openings exhibited significant reductions in stiffness, initial crack load, and ultimate load capacity compared to the solid beam, with larger openings causing up to 39% reduction in capacity. Strengthening with GFRP improved performance for small openings, increasing ultimate load by up to 21%, while rehabilitation after cracking also restored capacity but was less effective than pre-strengthening. For larger openings, GFRP wrapping provided only marginal gains (3–4%) and did not alter the shear failure mode, with debonding of FRP layers observed along diagonal cracks. The study concluded that GFRP sheets are effective for strengthening and rehabilitating RC beams with small openings, enhancing shear resistance and deflection control, but are inadequate for beams with larger openings where failure is governed by opening size.

[10] Ahmed et al. (2012) presented a comprehensive state-of-the-art review on reinforced concrete (RC) beams with web openings, focusing on their behavior, analysis, design approaches, and strengthening techniques. The study compiled findings from numerous experimental and analytical works, classifying openings as small or large based on size and structural response, and highlighting common shapes such as circular and rectangular. Various design methods were discussed, including the ACI approach, AIJ method, plasticity method, and strut-and-tie model for small openings, while the plastic hinge method was emphasized for large openings. The review noted that openings transform simple beam behavior into complex mechanisms, often leading to stress concentrations, early cracking, and Vierendeel action. Results from past studies showed that small openings (less than 25–40% of beam depth) could maintain beam-type behavior if properly reinforced, whereas larger openings significantly reduced stiffness and ultimate strength, altering failure modes. Strengthening techniques using fiber reinforced polymer (FRP) sheets and steel plates were found effective in restoring capacity, particularly for small openings, though debonding issues were reported. The authors concluded that careful detailing of reinforcement around openings, adherence to codal guidelines, and the use of external strengthening materials are essential to ensure ductility and prevent premature failure. They also identified gaps in comparative studies of design approaches and strengthening configurations, recommending further

research to establish unified guidelines for RC beams with web opening.

[11] Ahmed et al. (2016) investigated the repair effectiveness of damaged reinforced concrete (RC) beams with large rectangular web openings using externally bonded carbon fiber reinforced polymer (CFRP) and steel plates. Four beams were tested under four-point loading: one solid control beam and three beams with 160 × 400 mm rectangular openings located in the shear span. Two repair configurations were studied for each material—hexagonal and rectangular. The experimental program measured load capacity, deflection, strain distribution, and crack patterns before and after repair. Results showed that CFRP plates significantly improved load capacity and stiffness compared to steel plates, with rectangular configurations performing better than hexagonal ones. Specifically, CFRP rectangular plates increased load capacity by 43% over pre-repair values, while steel rectangular plates achieved a 30% improvement. Hexagonal configurations were less effective, with CFRP yielding 25% improvement and steel only 4%. Deflection reductions were also greater in rectangular configurations (up to 10%) compared to hexagonal ones (3–4%). The study concluded that externally bonded CFRP plates are more effective than steel plates for repairing RC beams with large web openings, and rectangular configurations provide superior performance by covering larger chord areas and controlling crack propagation.

[12] Thamrin et al. (2016) conducted an experimental study on the shear strength of reinforced concrete beams without stirrups, focusing on the influence of beam cross-section type (rectangular vs. T-section) and longitudinal reinforcement ratio. Six simply supported beams were tested under two-point loading until failure, with three rectangular and three T-beams designed at reinforcement ratios of 1%, 1.5%, and 2.5%. The study observed diagonal shear cracks as the primary failure mode, with flexural cracks preceding shear failure. Results showed that T-beams exhibited 5–25% higher shear capacity than rectangular beams due to flange contribution and increasing longitudinal reinforcement ratio enhanced shear strength while reducing the angle of diagonal cracks. Comparison with empirical equations (Zsutty, Niwa, Eurocode 2, and SNI) revealed that all conservatively estimated shear capacity, with test values 10–90% higher than theoretical predictions. The authors proposed a simple model to account for flange contribution in T-beams, confirming that flange geometry significantly influences shear stress distribution and crack propagation. The study concluded that T-beams without stirrups possess superior shear resistance compared to rectangular beams, and reinforcement ratio plays a critical role in both shear capacity and crack behavior.

[13] Nie et al. (2021) presented a theoretical study on the strength of reinforced concrete (RC) beams with fibre-reinforced polymer (FRP)-strengthened web openings. Recognizing that web openings reduce beam strength and stiffness due to loss of cross-sectional area and severed reinforcement, the authors proposed two analytical approaches: (i) an iterative numerical method based on plastic limit analysis, and (ii) a simplified closed-form strength model. The study verified these models against experimental data from eight full-scale RC T-section beams with FRP-strengthened rectangular openings tested under three-point bending. The specimens included large, medium, and small openings, strengthened with CFRP wraps and U-jackets anchored by spike anchors. Results showed that unstrengthened beams failed in shear with diagonal cracks, while FRP-strengthened beams exhibited ductile flexural failure characterized by four plastic hinges at chord ends. The iterative method provided accurate predictions of ultimate strength, while the simplified strength model offered practical design equations with acceptable accuracy. The study concluded that FRP strengthening can effectively restore the load-carrying capacity of RC beams with web openings, ensuring ductile flexural failure rather than brittle shear failure, and that the proposed strength model offers engineers a reliable tool for design applications.

[14] Özkılıç et al. (2022) conducted a comprehensive numerical study on the behavior of reinforced concrete (RC) beams with circular web openings strengthened using carbon fiber reinforced polymer (CFRP). Building upon earlier experimental work, the authors calibrated finite element models in ABAQUS against nine tested specimens and extended the analysis to 95 parametric models. The parameters investigated included opening diameter-to-beam height ratio

(D/H), concrete compressive strength, stirrup spacing, opening location, CFRP application type, ply orientation, and number of CFRP layers. Results showed that beams with small openings (D/H ≤ 0.3) retained ductility and could reach flexural capacity when strengthened, while larger openings (D/H ≥ 0.64) suffered significant reductions in strength and stiffness, with CFRP unable to prevent brittle shear-compression failure. CFRP strip strengthening (CFRP-1) improved load capacity moderately, but full wrapping (CFRP-2) provided better ductility and energy dissipation, especially for medium openings (D/H ≈ 0.44). The study concluded that CFRP strengthening is effective for small to medium openings, with U-wrapping recommended over full wrapping, but ineffective for large openings where diagonal compression failure dominates.

[15] Salih et al. (2021) carried out experimental and numerical investigations on the cyclic load behavior of reinforced concrete (RC) beams with rectangular web openings strengthened using externally bonded carbon fiber reinforced polymer (CFRP) sheets. Six full-scale beams were tested under reverse cyclic loading, including one solid control beam, one unstrengthened beam with opening, and four beams strengthened with CFRP in vertical and inclined U-wrap orientations. The study measured hysteretic performance, stiffness degradation, ductility, pinching width ratio, and energy dissipation. Results showed that unstrengthened beams with openings suffered severe shear-flexural cracks and stiffness loss, while CFRP strengthening significantly improved cyclic performance. Strengthened beams exhibited enhanced load-carrying capacity, with increases of 63.43% for openings in shear zones and 73% for openings in flexural zones compared to control beams. Numerical models using concrete damaged plasticity accurately simulated the hysteretic loops and failure modes, validating the experimental findings. The authors concluded that CFRP U-wrap strengthening around rectangular openings effectively restores stiffness, improves ductility, and enhances cyclic load resistance, making it a reliable retrofit technique for RC beams subjected to seismic-type loading.

[16] Al-Sulayfani et al. (2023) experimentally and analytically investigated the effect of web openings on the behavior of reinforced concrete (RC) deep beams and the enhancement provided by carbon fiber reinforced polymer (CFRP) laminates. Thirteen deep beam specimens (120 × 750 × 1800 mm) were tested under four-point loading, with openings of varying shapes (circular and square), sizes (230–370 mm), and locations (center, top, and bottom of shear span). CFRP laminates were applied at different orientations (0°, 45°, and 90°) to strengthen beams with circular openings, and two damaged specimens were repaired using CFRP. Results showed that openings reduced shear strength by 22–74%, stiffness by 11–53%, and toughness by 14–54%, with square openings causing greater strength loss than circular ones. CFRP strengthening improved shear strength by 17–48%, stiffness by up to 17%, and toughness by 4–20%, with the 45° orientation proving most effective. Repaired beams regained nearly 100% of their original capacity. Analytical predictions using the strut-and-tie method correlated well with experimental results (Pearson coefficient 0.96), confirming its reliability. The study concluded that CFRP laminates are effective for strengthening and repairing RC deep beams with openings, particularly when applied at 45°, and that square openings are more detrimental than circular ones.

[17] Hamid et al. (2024) investigated the strengthening of reinforced concrete (RC) beams with circular post-drilled openings in shear zones using externally bonded carbon fiber reinforced polymer (CFRP) sheets. Five beams of 150 mm width, 300 mm depth, and 1550 mm length were tested under four-point loading until failure. The specimens included one solid control beam, two beams with 100 mm diameter circular openings, and two beams with similar openings strengthened by CFRP U-wrap sheets. The study measured ultimate load capacity, deflection, strain distribution, crack propagation, and failure modes. Results showed that beams with openings experienced significant reductions in strength and stiffness compared to the solid beam, with two openings reducing capacity by up to 25%. Strengthening with CFRP sheets improved performance, delaying crack initiation, reducing deflection, and increasing ultimate load capacity by 4–14.5% compared to unstrengthened beams with openings. The authors concluded that CFRP strengthening is an effective repair technique for RC beams with post-drilled openings in shear zones,

preventing brittle shear failure and enhancing stiffness and ductility.

[18] Morsy et al. (2019) carried out an extensive experimental program to study the behavior of reinforced concrete (RC) beams with web openings and the effectiveness of different strengthening techniques. A total of 24 beams were tested under three-point loading, divided into two series. The first series examined the influence of opening shape (square, rectangular, circular), aspect ratio, and orientation on beam performance, while the second series investigated strengthening methods including internal steel reinforcement (ISR), internally embedded FRP rods (IER), near-surface mounted (NSM) laminates, externally bonded (EB) CFRP laminates, and steel box reinforcement. Results showed that circular openings caused the least reduction in load capacity compared to square and rectangular openings of equal area, as stress concentration at corners was minimized. Strengthening with CFRP laminates improved both strength and ductility, with near-surface mounted laminates and rods providing significant enhancement in shear and flexural zones. Steel box reinforcement was less effective due to weld failure under shear stresses. The study concluded that CFRP-based strengthening techniques are the most efficient for restoring strength and ductility in RC beams with openings, with NSM laminates and rods offering superior performance compared to conventional steel reinforcement.

[19] Kumar et al. (2013) experimentally investigated the behavior of reinforced cement concrete (RCC) beams with circular openings strengthened using carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) sheets. Ten beams were cast, including one solid control beam, one unstrengthened beam with circular post-opening, and eight beams strengthened with CFRP and GFRP sheets under different schemes: around the opening, inside the opening, inside and around the opening, and double-layer wrapping. All beams were simply supported and tested under two-point loading. The study evaluated load-carrying capacity, load-deflection behavior, and crack patterns. Results showed that the presence of circular openings reduced strength and stiffness significantly, with the unstrengthened beam losing about 37.6% of its capacity compared to the solid beam. Strengthening with CFRP sheets increased ultimate load capacity by 13.01–55.32%, while GFRP sheets achieved 8.13–45.56% improvement. Among all schemes, CFRP applied both inside and around the opening proved most effective, restoring flexural behavior and achieving the highest strength gain. The study concluded that CFRP sheets provide superior strengthening compared to GFRP, and the combined inside-and-around wrapping scheme is the most efficient for enhancing the performance of RCC beams with circular openings.

[20] Sweeney et al. (2020) presented a numerical investigation into the design of reinforced concrete (RC) beams with web openings, focusing on validating finite element (FE) models against experimental data. Using Ansys Mechanical APDL, five different FE models were developed, ranging from elastic beams without reinforcement to fully reinforced beams with varying web opening sizes (100×100 mm, 200×100 mm, 300×100 mm, and 300×150 mm). The models incorporated non-linear material properties for concrete and steel, and crack propagation was analyzed under four-point bending. Results showed that the FE models correlated well with analytical and experimental findings, particularly for large openings where ultimate load capacity reductions matched closely with experimental data. For smaller openings, numerical predictions differed by 55–56% compared to experiments, highlighting sensitivity in modeling assumptions. Overall, increasing web opening height to 60% of beam depth reduced ultimate load capacity by 75%, consistent with experimental studies. The authors concluded that Ansys can accurately simulate RC beams with web openings, providing engineers with a reliable tool for predicting strength, stiffness, and crack behavior, and recommended extending the work to model FRP strengthening of web openings.

[21] Vathsala et al. (2024) The literature on reinforced concrete (RC) beams, transverse openings are often introduced to accommodate essential utilities such as HVAC ducts, electrical lines, and plumbing systems, but these openings create stress concentrations that reduce shear strength and serviceability. Experimental investigations have shown that small circular

openings, with diameter-to-depth ratios less than 50%, can be managed effectively when special reinforcement is provided around the periphery, as such beams exhibit reduced deflection and improved crack control compared to solid beams. In a study where nine beams were tested under two-point loading, three solid beams acted as controls, three beams with pre-cut openings and reinforcement (BH) showed the least deflection, and the remaining beams with post-cut openings retrofitted using carbon fiber reinforced polymer (CFRP) sheets demonstrated enhanced ductility and effective arrest of shear cracks. The results confirmed that pre-planned openings with adequate reinforcement are the most reliable approach, while CFRP retrofitting serves as an efficient strengthening technique for post-formed openings, restoring load capacity and improving crack resistance. Thus, CFRP emerges as a superior retrofitting material, offering high strength-to-weight ratio and durability, making it a practical solution for RC beams with service-related openings.

[22] Osman et al. (2017) studied the shear behavior of reinforced concrete (RC) beams with circular web openings without additional shear reinforcement, using both experimental testing and finite element (FE) modeling in ANSYS 14.5. Four beams were tested under two-point loading: three solid control beams with varying shear span-to-depth ratios (1.0d, 2.0d, and 2.5d) and one beam with two circular openings (130 mm diameter, opening-to-depth ratio 0.5) placed symmetrically in the shear spans. The FE model was validated against experimental results and extended to 31 specimens for parametric analysis. Results showed that openings located in high shear regions significantly reduced shear strength and caused premature brittle shear failure. The beam with openings (BS2O) exhibited a 30% reduction in capacity compared to its solid counterpart (BS2), failing at 93 kN versus 132 kN. Crack widths were larger in beams with openings, reaching 3.81 mm at failure. The FE simulations closely matched experimental load-deflection behavior, with ultimate loads differing by less than 6%. The authors concluded that openings in critical shear zones severely compromise beam performance, and the validated FE models provide a reliable platform for predicting shear strength and failure modes of RC beams with different opening geometries.

[23] Thakur et al. (2023) conducted an experimental study on the behavior of RCC beams with circular openings in bending and shear zones, strengthened using glass fiber reinforced polymer (GFRP) sheets. Nine beams of 150 × 150 mm cross-section and 700 mm span were tested under two-point loading in a universal testing machine. One solid beam acted as a control, two beams had unstrengthened post-openings (one in shear zone and one in bending zone), while six beams with openings were strengthened using different GFRP schemes: around the opening, inside the opening, and both inside and around the opening. Load-deflection behavior, crack initiation, and failure modes were recorded. Results showed that beams with openings exhibited reduced strength and stiffness compared to the solid beam, with shear zone openings being more critical. Strengthening with GFRP sheets improved performance, with the “around and inside” scheme proving most effective, increasing ultimate load capacity by 20.55% compared to unstrengthened beams. The study concluded that GFRP sheets are efficient for restoring strength in RCC beams with circular openings, particularly when applied both inside and around the opening, thereby enhancing load capacity and delaying shear failure.

[24] Balamuralikrishnan et al. (2009) investigated the flexural behavior of reinforced concrete (RC) beams strengthened with externally bonded carbon fiber reinforced polymer (CFRP) fabrics. Ten beams of size 150 × 250 × 3200 mm were cast, including two control beams and eight strengthened beams with CFRP applied in single and double layers at the soffit. The beams were tested under monotonic static and cyclic compression loading, and their performance was compared with finite element analysis (FEA) using ANSYS. Parameters studied included flexural strength, stiffness, ductility, energy absorption, composite action, and crack patterns. Results showed that CFRP strengthening significantly enhanced flexural capacity, with single-layer strengthening increasing strength by 18–20% and double-layer strengthening achieving 40–45% improvement. Strengthened beams exhibited reduced deflections (up to 80% lower at ultimate load), improved stiffness, and maintained composite action without premature debonding. Numerical predictions closely matched experimental outcomes, confirming the reliability of the FEA model. The study concluded that CFRP

fabrics are highly effective for flexural strengthening of RC beams, with two layers recommended for optimal performance in terms of strength, ductility, and durability.

[25] Hieu et al. (2024) carried out an experimental study on the effectiveness of strengthening reinforced concrete (RC) beams with openings in the shear span using carbon fiber reinforced polymer (CFRP) sheets. Six beams of 150 × 250 mm cross-section and 850 mm length were tested under three-point bending with a shear span-to-depth ratio of 1.48. One solid beam served as the control, while five beams had circular (110 mm diameter) or rectangular (80 × 120 mm) openings, with some strengthened by CFRP sheets applied vertically on the sides or fully wrapping the chords. Results showed that unstrengthened beams with openings suffered significant reductions in shear strength and stiffness, with circular openings causing a larger decrease (57.3%) compared to rectangular openings (29.1%). CFRP strengthening provided modest gains in shear resistance (4.7–7.8%) but notably improved stiffness and delayed diagonal crack propagation. However, strengthening circular openings with CFRP sheets bonded only on two sides was found ineffective in restoring shear capacity. The study concluded that while CFRP sheets enhance stiffness and crack control, their effectiveness in shear strengthening depends strongly on opening geometry and reinforcement configuration, with rectangular openings responding better to CFRP confinement than circular ones.

A. Summary of Literature Review

Literature indicates that post-formed circular openings in RC beams cause significant shear capacity reductions, often exceeding 35% due to disrupted load paths, requiring rehabilitation to restore structural integrity. Externally bonded CFRP, particularly in optimized orientations, effectively mitigates this damage by enhancing load capacity and ductility, though failure is often dominated by CFRP debonding.

B. Research Gap

From the literature review, the following observations were made:

1. Most studies overlook that drilling circular openings cuts existing stirrups. Limited research exists on how CFRP spike or fan anchors can compensate for this loss in high-stress regions around the opening.
2. Existing studies mainly focus on small-scale beams. There is a lack of understanding of how shear capacity and CFRP effectiveness vary with increasing beam size and larger openings (greater than 40% of web depth), especially at different locations.
3. Most research uses monotonic loading, with little focus on fatigue or cyclic behavior. The bond performance of CFRP around curved openings under such conditions remains insufficiently studied.

V. CONCLUSION

The reviewed literature consistently establishes that the presence of post-formed circular openings in RC beams leads to significant reductions in shear strength, stiffness, and overall structural integrity, often resulting in premature and brittle failure modes. Experimental and numerical studies across multiple researchers have shown that unstrengthened beams with openings may lose up to 30–40% of their load-carrying capacity compared to solid beams, with accelerated crack initiation and propagation. However, the application of externally bonded CFRP sheets has been repeatedly validated as an effective strengthening technique, capable of restoring lost shear capacity, improving ductility, and ensuring safer failure mechanisms. Strengthening schemes such as U-wrapping or full encasement around openings have proven particularly efficient in redistributing stresses and delaying shear cracks. Collectively, the literature confirms that CFRP composites provide a codally compliant, sustainable, and high-performance solution for retrofitting RC beams with service-related openings, thereby bridging the gap between structural safety requirements and practical construction needs. This foundation underscores the relevance of the present experimental study, which builds upon prior findings to further quantify the effectiveness of CFRP in mitigating the adverse effects of post-formed openings in shear zones.

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