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Experimental Studies on Rounded Rectangular Opening in Beams

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Abstract: This paper provides a comprehensive overview of the extensive body of research pertaining to the strengthening of beams with openings using Fiber Reinforced Polymers (FRP). Openings in structural beams, necessitated by functional requirements such as accommodating services or architectural designs, introduce complexities that demand specialized strengthening techniques to ensure structural integrity and performance. The challenges associated with beams featuring openings, ranging from the reduction in load-carrying capacity to potential stress concentration. It then delves into the evolution of FRP materials and solution for retrofitting and enhancing structural members, including Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP). A critical analysis of the existing research explores various strengthening techniques involving FRP laminates and wraps applied externally, internally, or in combination around openings. The review also discusses the influence of factors such as adhesive systems, fiber orientation, and installation methods on the effectiveness of FRP strengthening. Identifies research gaps and potential areas for further exploration, ultimately serving as a valuable resource for researchers, and practitioners involved in the rehabilitation and enhancement of structural systems with openings.

Keywords: CFRP, GFRP laminates, RC beams, opening of beams, failure crack pattern, strengthening of beams.

I. INTRODUCTION

An opening in a reinforced concrete beams web causes a variety of issues with the behaviour of the beam, including the reduction in the stiffness, excessive cracking, excessive deflection, and reduce in strength. A "waste space" or "dead space" is created beneath the bottom face of the beam where ducts and pipes are typically located, hidden from view by a false ceiling. The use of openings in RC beams, however, may result in a significant reduction in the flexural and shear capacities because of stress concentration at the corners of the openings. Transverse openings in beams come in a variety of sizes and shapes. The unusual design of a multi-story high-rise building.

This experimental study is considering a circular opening. Even though there are many kinds of openings, circular and rectangular openings are the most frequently used. While rectangular openings are frequently used as air conditioning ducts in beams, circular openings are required to accommodate pipes services like plumbing and electrical supply. The strengthening of RC beams with openings that effectively increased load capacity has been studied by numerous researchers. Numerous strengthening techniques were recommended to increase the shear capacity and restore the strength of the beams with openings.

FRP has a significant role in increasing strength of the structures. The reinforced concrete beams with openings can be strengthened by CFRP sheets, GFRP sheets, laminates, rods, fabrics, and other materials can be used to strengthen the reinforced concrete beams with openings. The load carrying capacity of the reinforced concrete beams with openings increases when strengthened externally with CFRP sheets in RC beams.

II. CLASSIFICATION OF OPENINGS THROUGH BEAMS

Transverse openings in beams can be classified based on their different sizes and shapes, including rounded-rectangular, elliptical, rectangular, round, diamond, trapezoidal, and irregular shapes. Among these, rectangular and circular designs are the most employed. Circular apertures are particularly advantageous for accommodating service pipes, such as those used for plumbing and electrical supplies.

Additionally, rounding off the corners of rectangular apertures can reduce stress concentration at the edges, thereby extending the beam's service life and minimizing the occurrence of fractures.

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III. LITERATURE REVIEW

Mohammed J. Altaee (1): In this study, investigated the use of carbon fiber reinforced polymer (CFRP) for strengthening steel beams with web openings. The introduction of web openings in steel beams is common in practice to accommodate additional services in buildings. However, these openings can reduce the strength and stiffness of the beams. Traditionally, additional steel plates are welded or bolted to the beams to strengthen them. This study focused on using CFRP as a novel strengthening method due to its ease of handling, superior strength-to-weight ratio, and corrosion resistance. The researcher conducted an experimental study using four full-scale universal beams, which were tested under 6-point bending. They also modelled equivalent test series without CFRP strengthening using finite element analysis. The results showed that CFRP strengthening was effective, with load-carrying capacity increases of 5% to 20% compared to the unaltered beams. Different failure modes were observed depending on the location and size of the openings. The study demonstrated the feasibility of using CFRP to strengthen steel beams with web openings, offering advantages over traditional steel plates. This method has the potential to extend the service life of structures and improve their load-carrying capacity.

Wang Wenwei (2): Six reinforced concrete beams with flexure reinforcement made with carbon fiber reinforced polymer (CFRP) laminates were evaluated under various sustaining loads. The primary objective of the test is to investigate the effects of initial load and load history on the ultimate strength of CFRP laminates externally bonded to reinforced concrete beams. Different degrees of sustaining load at the point of strengthening and load history are the key experimental conditions. A theoretical model for the flexural behavior of the strengthened reinforced concrete beam is also constructed in order to quantitatively explain the experimental data. According to test results in this study, sustaining load levels at the time of strengthening have a significant impact on the ultimate strength of strengthened reinforced concrete beams. Regardless of the load history at the time of strengthening, if the initial load is essentially the same, the final strength of reinforced concrete beams enhanced with CFRP laminates is essentially the same.

Rania Salih (3): In this study, an experimental investigation of the cyclic behaviour of a reinforced concrete (RC) beam with apertures reinforced with carbon fiber-reinforced polymers (CFRPs) was conducted. To assess the optimum resistance, secant stiffness, strength degradation, ductility, energy dissipation capacity, and behaviour of the specimens' failure mode under cyclic load, seven rectangular RC beams were cast and strengthened through external bonding of CFRP sheets around the beam web opening with various orientations. The studies used six beams built with circular web openings commonly situated in the middle of the beam and close to the supports, along with one solid beam without an opening (i.e., control specimen). Two of the six examples with opening configuration—two beams—were left un-fortified, and the other four specimens—four specimens with inclined and vertical scheme orientation—were strengthened with two layers of FRP sheets. Experiments were used to validate the results of the finite element modelling analysis, which was carried out numerically using the ABAQUS program. The introduction of FRP sheets significantly changed the cyclic behaviour of RC beams, as shown by the results, which increased maximum strength and ultimate displacement to roughly 66.67% and 77.14%, respectively. The validated finite element models provide a computational framework for useful parametric analyses, where the effects of bond length and opening size are examined.

Ahmed A. Elansary (4): The behaviour of RC beams was experimentally investigated in this work to determine the impact of employing web holes close to the supports. It was anticipated that adding outside Carbon Fibre Reinforced Polymer (CFRP) sheets to the openings would reinforce them and improve how these beams behaved. Six RC beams with various opening sizes were cast, tested under four-point stresses close to the supports. The crack patterns, deflections, and stresses of the six beams were compared to those of a solid RC beam without an aperture used as a reference. All of the tested beams had a total and clear span of 2200 mm and 2000 mm, respectively, and a rectangular cross section of 150x300 mm. Analytical and code equations were used to compare the measured load deflection and shear strength of the experimental beams to those expected values. According to the experimental findings, substantial holes reduced RC beams' shear capacity by up to 35% when compared to solid beams. Additionally, it was shown that using CFRP sheets to reinforce the web opening increased the shear capacity of comparable beams by 21% to 28%. At failure, the yielding strain was not reached by the longitudinal bars' and stirrups' near-opening strains. Layer-by-layer analysis was successful in predicting the load-deflection behaviour of the reference beam as well as those with openings since the opening had no effect on the overall load deflection behaviour of the beams.

Tarek Almusallam (5): This study examines how reinforced concrete (RC) beams with wide rectangular web holes behave when they are reinforced with fiber reinforced polymer (FRP). Seven RC beams, split into two different groups, were tested. The first set consists of two un-strengthened beams that underwent four-point bending tests, one with a big rectangular web opening and the other solid in the pure flexure zone. Five beams were evaluated in the second group using the centre-point loading. They were composed of a reference solid beam and four beams having sizable rectangular web holes in the maximum-moment zone. Two of the four beams with openings were left unreinforced, while two other

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beams underwent two distinct FRP reinforcement strategies. A web opening with a length of 450 mm and a depth of 225 mm was used in the test program. To avoid the issue of galvanic corrosion that might arise when metals are connected to CFRP, it was decided to use GFRP rather than CFRP. This method for strengthening can now be used in the field safely. Finite Element Modelling was employed to finish the job. The flexural strength of un- and FRP-strengthened RC beams with web holes in the flexure zone may be predicted using the FE modelling used in this study. This proves the efficacy of the modelling strategy, which can be relied upon in upcoming research on the application of FRP for RC structural parts. If the depth of the top chord is equal or greater than to the depth of a concrete stress block at ultimate state, the opening in RC beams having openings in the pure flexure zone has no effect on their ultimate capacity.

Tamer El Maaddawy (6): This report presents the findings of a research study focused on the potential application of externally bonded carbon fiber reinforced polymer (CFRP) composite sheets to enhance the strength and performance of reinforced concrete (RC) deep beams containing openings. Thirteen deep beams with openings were constructed and subjected to four-point bending tests. These beams had dimensions of 80 x 500 mm and a total length of 1200 mm, with two square openings symmetrically placed in each shear span. The research investigated various parameters, including the size and location of the openings, as well as the presence of CFRP sheets. The study revealed that the structural behaviour of RC deep beams with openings primarily depended on the extent of interruption of the natural load path. Notably, externally bonded CFRP shear strengthening around the openings proved highly effective in increasing the shear strength of these beams, resulting in strength gains ranging from 35% to 73%. Furthermore, the report discussed an analytical model for predicting shear strength, and while there was some variation between experimental and analytical results, it demonstrated that the analytical procedure could reasonably predict the shear strength of RC deep beams with openings strengthened by CFRP sheets. Overall, this research highlights the potential of CFRP strengthening as a viable solution for upgrading the performance of RC deep beams with openings, with significant implications for structural engineering and construction practices.

S.C. Chin (7): This report delves into the examination of the strengthening of reinforced concrete (RC) beams featuring large circular and square openings located at the flexure zone through the utilization of Carbon Fiber Reinforced Polymer (CFRP) laminates. The comprehensive study included tests on five beams subjected to failure under four-point loading, with a primary focus on understanding their structural behaviour. This encompassed analyzing crack patterns, failure modes, ultimate loads, and load-deflection characteristics. In the case of un-strengthened beams with large circular openings, a notable reduction in both capacity and stiffness was observed, coupled with increased cracking and deflection. The situation became more severe with large square openings, leading to even more significant reductions. The predominant failure mode for un-strengthened beams was identified as flexural failure. However, the introduction of CFRP laminates to strengthen these beams yielded remarkable results. The laminates proved highly effective in restoring the beam capacity, particularly in cases with large circular openings. Notably, the ultimate capacity of these beams was increased by an impressive 70%, indicating substantial over-strengthening. On the other hand, when applied to beams with large square openings, CFRP laminates demonstrated a 10% increase in flexural strength, showing their effectiveness in this configuration as well. The stiffness of the beams with CFRP reinforcement showed a 33% increase for large circular openings and a 17% increase for large square openings compared to their un-strengthened counterparts. Additionally, CFRP application significantly reduced excessive cracking and deflection in both cases. The study underscores the importance of choosing the appropriate opening shape and the precise configuration for CFRP strengthening to achieve optimal results. Although square openings exhibited a more detrimental impact on structural capacity, CFRP reinforcement still provided substantial improvements, underscoring the effectiveness of this technique in restoring the structural integrity of RC beams with large openings.

Nurul Izzati Rahim (8): In this experimental study, the structural behaviour of deep beams in reinforced concrete (RC) with web openings, reinforced using externally connected carbon fiber reinforced polymer (CFRP) composites in the shear zone, was thoroughly investigated. The research aimed to understand the complex interplay of factors influencing these deep beams, including their failure modes, cracking patterns, load-deflection responses, stress concentrations, and reinforcement factors. Nine RC deep beams with varying opening sizes and different numbers of CFRP layers were subjected to static four-point bending tests until they reached failure. Notably, the results revealed a significant relationship between opening size and shear strength reduction, with larger openings leading to a more substantial decrease in load-carrying capacity, up to 30%. Furthermore, the addition of CFRP layers enhanced the beams' shear behaviour, with the optimal number of CFRP layers varying based on the opening size—two layers proving most effective for 150 mm openings and three layers for 200 mm openings. These findings shed light on the critical role of CFRP strengthening in deep beams and can inform structural engineers in optimizing their designs for improved performance and safety. Moreover, the study suggests the use of modified theoretical models for predicting shear capacity and highlights avenues for future research, including exploring different strengthening materials and shapes for deep beams with openings.

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Fatma M. F. Agag (9): The comprehensive research investigated the efficiency of various strengthening techniques for reinforced concrete beams with openings, shedding light on critical findings that have significant implications for structural engineering and design. Thirteen beams with openings at different locations were tested under four-point bending, with the study considering techniques applied both before and after casting, including diagonal steel bars, upper and lower additional steel bars, and externally bonded carbon fiber reinforced polymers (CFRP) sheets. In contrast, the study revealed that externally bonded CFRP sheets, while a widely used strengthening technique, did not consistently yield the desired results. In some cases, CFRP sheets led to reduced load-carrying capacity, with reductions ranging from 3.15% to 19.78% when compared to control beams. This finding suggests that the effectiveness of CFRP sheets may be contingent on factors such as opening location and structural configuration. Moreover, the research delved into the unique challenges posed by beams with openings in shear zones near supports. Beams strengthened with diagonal steel bars and upper and lower steel bars proved highly effective in augmenting load capacity in such scenarios, with enhancements ranging from 10.9% to 50.46%, depending on the timing of reinforcement application. However, externally bonded CFRP sheets displayed suboptimal performance in shear zone openings.

K. Preethi (10): This research investigates the behaviour of reinforced concrete deep beams with openings, a common structural element used in various applications, including offshore structures, fortifications, and buildings. The presence of openings for doors, windows, or utility services can weaken these beams, posing safety risks. The study involves casting and testing five such beams with openings to understand their structural performance. The findings reveal that the behaviour of deep beams with openings largely depends on how these openings affect the load path. The introduction of externally bonded Glass Fiber Reinforced Polymer (GFRP) sheets effectively enhances the shear strength of these beams, with improvements ranging from 68% to 125%. Finite Element Modelling (FEM) using ANSYS was used to validate experimental results. The research highlights the potential of GFRP sheets in strengthening deep beams with openings and demonstrates that closely spaced GFRP reinforcement offers better results than widely spaced reinforcement. The study contributes to the understanding of these structural elements, which play a vital role in various engineering applications.

Soo-yeon Seo (11): This study presents an experimental investigation into the flexural strength of reinforced concrete (RC) beams enhanced with partially de-bonded near-surface-mounted fiber-reinforced polymer (FRP) strips of various de-bonded lengths. Specifically, the study explores the influence of the de-bonded region at the central part of the beam and the impact of using triple NSM FRP strips compared to single strips. The flexural strength of the RC members retrofitted with partially de-bonded NSM FRP strips is evaluated using established strength equations. The findings suggest that the NSM FRP retrofit method can provide superior retrofit capacity compared to the existing external bonding method, primarily due to the ability to secure high bond capacity by mounting FRP strips vertically. Moreover, distributing NSM FRP strips in triple lines enhances the bond strength, allowing for a relatively high strength gain. The report emphasizes the importance of careful consideration when using thin FRP strips in full bonding NSMR to prevent yield strength reduction. The study demonstrates that de-bonded regions in the central part of the flexural member can improve deformation capacity, potentially enabling the design of ductile fractures in structural members. Further research is recommended to explore the effect of de-bonding with different types of FRP and to interpret the impact on flexural displacement.

Ghada Gamal Ahmed (12): This research addresses the critical challenge of creating openings in the shear zone of casted reinforced concrete beams, a problem that significantly impacts building safety and project schedules. The study comprehensively investigates the behaviour of these beams, considering various parameters like opening location, cross-section shape, the number of carbon fiber reinforced polymer (CFRP) layers, and concrete compressive strength. Employing Finite Element Analysis with ANSYS 15.0, the research rigorously validates its models against experimental data and reaches several key conclusions. Firstly, the study reveals that the precise location of openings has a substantial impact on failure load and displacement, with openings in the shear span leading to a notable reduction in failure load, approximately 47.67%. Secondly, the choice of beam cross-section shape emerges as a crucial factor, showing that L-section beams exhibit different behaviour compared to rectangular beams, particularly when openings are involved. Furthermore, enhancing concrete compressive strength from 25 to 45 MPa results in a significant increase in shear strength capacity, approximately 23%.

The study also underscores the effectiveness of ANSYS 15.0 as a valuable tool for simulating and analysing reinforced concrete beams, producing results consistent with empirical experiments. Lastly, the research highlights that higher concrete compressive strength enhances overall beam rigidity, potentially reducing the necessity for post-casting strengthening measures. These findings collectively contribute valuable insights into optimizing the design and construction of reinforced concrete beams with openings, fostering both safety and efficiency in structural engineering projects.

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IV. CONCLUSION

In conclusion, the collective findings from these diverse research studies on beams with openings underscore the promising potential of carbon fiber reinforced polymers (CFRP) as a valuable tool for strengthening structural elements. By systematically investigating the impact of openings' size, location, and different strengthening techniques, these studies offer substantial insights to structural engineers and designers. While CFRP has demonstrated effectiveness in many cases, it's crucial to note that its performance can vary based on factors such as opening location and structural configuration. This suggests that thoughtful design and precise application of CFRP or alternative strengthening methods are essential to achieve optimal results and enhance the load-bearing capacity and overall structural integrity of beams with openings. Furthermore, these Studies highlight the difficulties posed by openings in shear zones near supports, emphasizing the need for tailored strengthening strategies. For instance, the use of diagonal steel bars and upper and lower steel bars has shown remarkable effectiveness in augmenting load capacity in such scenarios.

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