Journal of Science and Technology in Civil Engineering, HUCE, 2024, 18 (1): 1–11

EXPERIMENTAL STUDY ON THE EFFECTIVENESS OF STRENGTHENING OF REINFORCED CONCRETE BEAMS WITH OPENING IN SHEAR SPAN USING CFRP SHEETS

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Article history:
Received 12/10/2023, Revised 12/3/2024, Accepted 20/3/2024

Abstract

In reinforced concrete beams, the opening is frequently required for the passage of utility ducts and/or pipes. The presence of such web openings leads to a reduction of the strength and stiffness of the beam. To ensure the safety of the reinforced concrete beam, a strengthening system around the opening is necessary. This paper aims to contribute to a better understanding of the shear behavior of reinforced concrete beams with openings in the shear span, strengthened with Carbon fiber-reinforced polymer (CFRP) sheets. The study is based on an experimental program carried out on six beams. All beam specimens were 850 mm long with a cross-section of 150 × 250 mm and a shear span to beam depth ratio (a/d) of 1.48. One beam without any openings served as the control specimen, while the remaining five beams featured circular or rectangular openings within the shear span and with/without shear strengthening using CFRP sheets around the openings. The test results obtained from this experimental program provide insights into the shear behavior of beams with openings, both with and without strengthening using CFRP sheets. Additionally, the potential advantages and effectiveness of employing CFRP strengthening techniques for opening strengthening are investigated and discussed.

Keywords: beam; opening; shear; failure; strengthening; CFRP sheets.

https://doi.org/10.31814/stce.huce2024-18(1)-01

1. Introduction

In reinforced concrete (RC) structures, the inclusion of openings in the beams is frequently used to accommodate essentials such as electricity, water supply systems, air conditioning, telephone lines, internet cables... These openings can take various shapes, including square, rectangular, and circular, and are classified as small or large openings based on the ratio of the opening height to the beam depth. For circular openings, if the ratio exceeds 40%, it is classified as a large opening. Similarly, for square or rectangular openings, if the ratio exceeds 25%, it is considered a large opening [1, 2].

The incorporation of openings in reinforced concrete structures provides several benefits, including the avoidance of additional story heights required for accommodating ducts and pipes. By incorporating these openings, the overall height of the building can be reduced, resulting in lower loads on the structural members and foundation. This reduction in loads contributes to a more economical design of the building, leading to cost savings. This concept has been studied and supported by references [1–3], which further emphasize the advantages of utilizing openings in reducing building height and achieving structural and economic efficiency. When an opening is planned before casting the beam, it is possible to arrange internal deformed steel bars around the opening to address the structural requirements. However, in existing RC beams where ducts or pipes need to be installed but no pre-formed openings exist in the beams, creating openings in the beam has proven to be an

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efficient solution, which has been implemented in numerous real projects. It is important to note that this solution results in a reduction of the cross-sectional area, shear capacity, and stiffness of the RC beams. There have been numerous experimental and numerical research dedicated to investigating the behavior of RC beams with openings. These studies have examined various aspects including the shear span to beam depth ratio, opening geometry, concrete compressive strength, flexural reinforcement ratio, loading conditions, and strengthening techniques [1–7]. The findings from these studies consistently show that the introduction of an opening in the web of an RC beam leads to the early formation of diagonal cracks and a substantial reduction in both the shear capacity and stiffness of the beam. This reduction in shear capacity and stiffness highlights the detrimental effect of openings on the structural performance of RC beams.

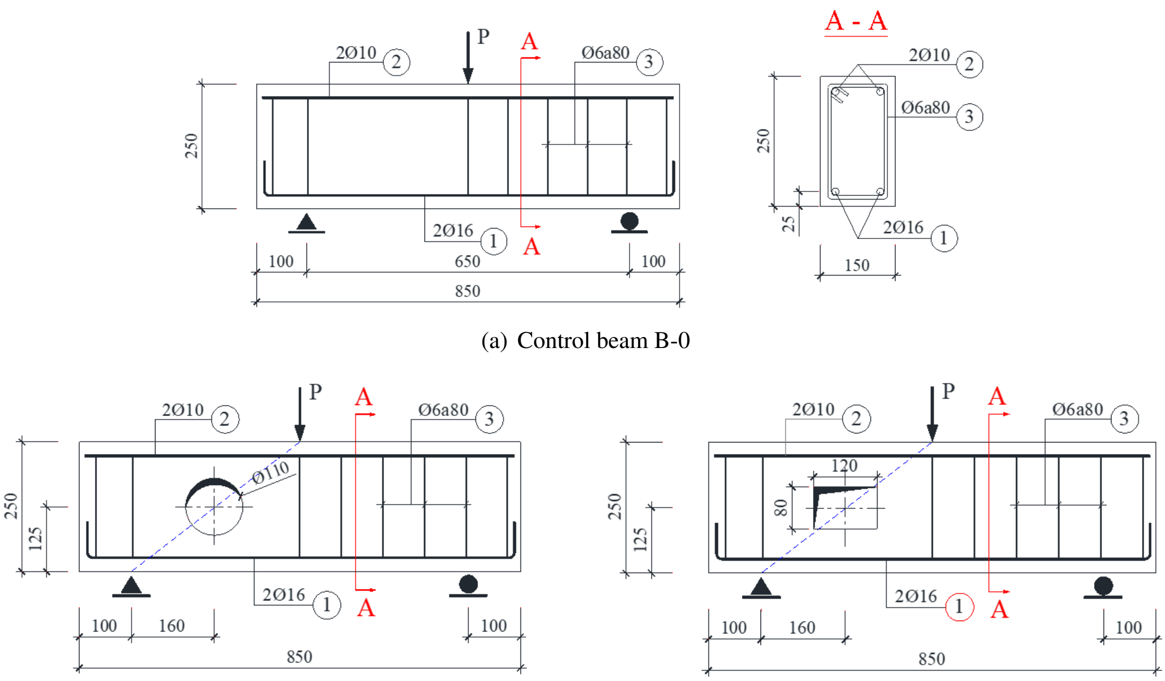
To ensure the load-bearing capacity of the beam after creating an opening, a strengthening system is necessary. This typically involves the application of external reinforcement, such as steel plates or fiber-reinforced polymer (FRP) materials, around the opening. Among the various options, the use of Carbon fiber-reinforced polymer (CFRP) sheets has gained significant popularity as a retrofit technique for strengthening RC structures. Externally bonded CFRP sheets have proven to be effective in various types of structures, including columns, beams, walls, slabs, and more. The application of external CFRP strengthening can be categorized as flexural strengthening, improving the ductility of compression members, and shear strengthening [8–15]. In the context of shear strengthening for RC beams with openings, numerous researchers in the literature have reported on the effectiveness of externally bonded CFRP sheets in improving the performance of the RC beams [1, 16–24]. Mansur et al. [1] tested three T-section RC beams to examine the potential use of CFRP sheets as a strengthening solution to upgrade RC beams with openings. One of the three beams had no web opening and served as the control specimen. One of these two beams with a web opening was un-strengthened while the other one was strengthened using bonded FRP plates around the web opening. The control and the strengthened beams failed in a flexural mode due to the crushing of the compressive concrete at mid-span while the beam with an un-strengthened circular web opening failed by the formation and propagation of a diagonal shear crack in each shear span passing through the opening. Maddawy and Sherif [15] conducted experimental research to examine the potential use of CFRP sheets as a strengthening solution to upgrade RC deep beams with openings. A total of 13 deep beams with square and circular openings were constructed and tested under four-point bending. Test parameters included the opening size, location, and the presence of the CFRP sheets. Externally bonded CFRP shear strengthening around the openings was found very effective in upgrading the shear strength of RC deep beams. Campione and Minafo [16] test twenty reinforced concrete small-scale deep beams with or without openings and having small shear span-to-depth ratios. The results showed that the location of the opening and the reinforcement arrangement significantly influence the behavior of the RC beams and the shear strength. Nie et al. [17] conducted a study on the finite element modeling of RC beams with strengthened rectangular openings through the dynamic analysis approach using ABAQUS. By using this FE approach, parametric studies are conducted for the design of the CFRP strengthening for a typical web-opening weakened RC beam, and a reliable CFRP strengthening is recommended for use in practice.

This paper focuses on the shear behavior of RC beams with an opening in shear span and a small shear span to beam depth ratio a/d of 1.48, which is less than 2, containing a rectangular of a circular opening and strengthened in shear with CFRP sheets. The experimental program included testing six RC beams with circular or rectangular openings in shear span, both strengthened and un-strengthened with CFRP sheets. This research aims to provide experimental evidence to assess the effectiveness of CFRP sheets in improving the shear capacity of RC beams with openings in the shear span. The obtained results additionally contribute to expanding the test database of shear strengthening of RC beams with openings using externally bonded CFRP sheets. They also assist practicing engineers in understanding the interaction between the opening shape, the strengthening configuration, the failure mode, and the gain in shear capacity. The findings of this study are expected to support the development of design guidelines for the use of CFRP sheets to prolong the service life of existing RC structures.

2. Experimental research

2.1. Specimen and material properties

A total of six test specimens were designed as simply supported RC beams with a cross-section size of 150 × 250 mm and a length of 850 mm. The details of the test specimens, including reinforcement layout and CFRP strengthening, are provided in Fig. 1. The test specimens are summarized in Table 1, which consists of one control specimen without any openings or strengthening, and five beams with circular and rectangular openings, both strengthened and unstrengthened with CFRP sheets around the openings.



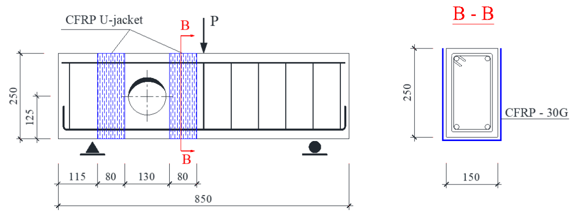
(a) Control beam B-0

(b) Beam with circular opening B-1.1

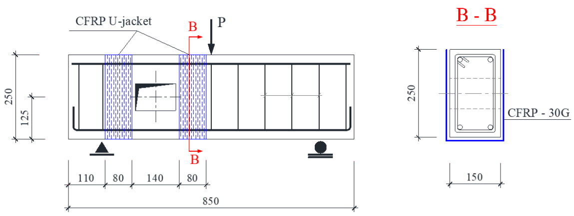
(c) Beam with rectangular opening B-2.1

Figure 1. Reinforcement details of test beam specimens

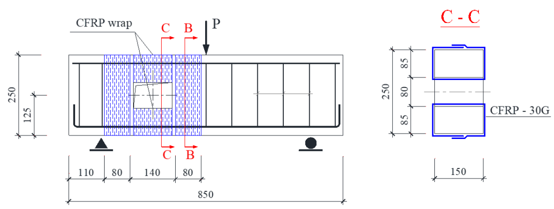
The parameters studied in this research included the shape of the opening (circular and rectangular) and the effect of CFRP sheet strengthening. The test specimens were subjected to three-point bending, with an effective span of 650 mm and a short shear span of 325 mm. The design of the specimens aimed to induce shear failure before any flexural distress occurred. Each beam had a main tensile steel reinforcement area of 401.9 mm^2, comprising two 16 mm diameter deformed bars with a yield strength of 380 MPa. The compression steel reinforcement consisted of two 10 mm diameter deformed bars. Shear reinforcements were not utilized in the shear span with openings to investigate the effect of the openings. Detailed information about the test specimens is provided in Fig. 1 and Fig. 2.



(a) Beam B-1.2: vertical strengthening at two sides of circular opening



(b) Beam B-2.2: vertical strengthening at two sides of rectangular opening



(c) Beam B-2.3: vertical strengthening at two sides and chord of rectangular opening

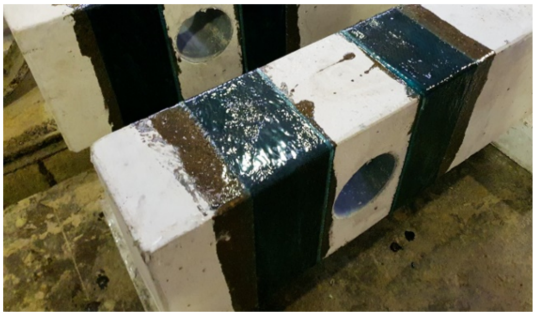
Figure 2. Details of test beam specimens strengthened with CFRP sheets

Table 1. Test specimens

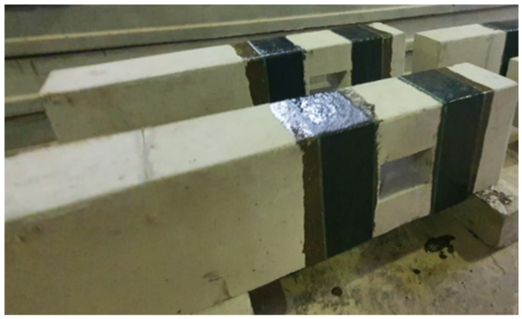
Beam designation	Specification
B-0	Control beam – No opening and not strengthened
B-1.1	Beam with circular opening, not strengthened
B-1.2	Beam with circular opening, strengthened using CFRP sheet
B-2.1	Beam with rectangular opening, not strengthened
B-2.2	Beam with rectangular opening, strengthenged using CFRP sheet
B-2.3	Beam with rectangular opening, strengthenged using CFRP sheet

Regarding the openings, the rectangular opening had dimensions of 80 × 120 mm, while the circular opening had a diameter of 110 mm. These dimensions were chosen to ensure that both openings had the same area. The center of the openings in all test beams was positioned at the center of the shear span region and aligned with the natural load path, which is the line connecting the load and support points. The circular opening was created by inserting a circular polyvinyl chloride (PVC) pipe into the beam before concrete casting, while the square rectangular opening was formed by using a plywood box.

Fig. 3 illustrates the arrangement of the CFRP shear strengthening system employed around the opening. In the case of specimens B1.2 and B2.2, a single layer of vertical CFRP U-jacket with a thickness of 0.167 mm and a width of 80 mm was utilized to strengthen the beam on both sides of the opening. For specimen B2.3, an additional layer of CFRP sheets with the same thickness was employed to fully wrap the top and bottom chords. The installation of the CFRP strengthening system was performed using the wet-layup process.



(a) Beam B-1.2



(b) Beam B-2.2

(c) Beam B-2.3

Figure 3. The layout of CFRP shear strengthening system

All beam specimens were cast using the same batch of concrete mix, the composition of which is provided in Table 2. The average compressive strength of the concrete cylinders, measured at 28 days, was found to be 34.7 MPa.

Table 2. Mixture proportions for 1m^3 of concrete (kg/m^3)

Cement PCB40	Sand	Coarse aggregate	Water
365	680	1230	175

The CFRP sheets utilized in this study were unidirectional. The mechanical properties of the CFRP sheets are presented in Table 3.

Table 3. Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate tensile elongation (%)
0.167	240	3400	1.6

2.2. *Test setup and instrumentations*

Fig. 4 depicts the typical test setup employed for the experimental investigation, while Fig. 5 illustrates a test in progress. All six beam specimens underwent testing using a three-point bending configuration. The load was applied at the mid-span of the beam using a hydraulic jack. An electronic force measuring instrument (load cell) was utilized to determine the applied load. Three linear variable differential transformers (LVDTs) with an accuracy of 0.001 mm, designated as LVDT-1, LVDT-2, and LVDT-3, were positioned at the two supports and in the middle of the test specimen, respectively. These LVDTs were employed to measure the displacement of the beams during loading. The maximum deflection of the middle cross-section of the test specimens was determined based on the measurements obtained from the LVDTs. The force and displacement measuring instruments were connected to a TDS 530 data logger, enabling continuous and automatic recording of experimental data at one-second intervals. The tests were conducted until the failure of the specimens.

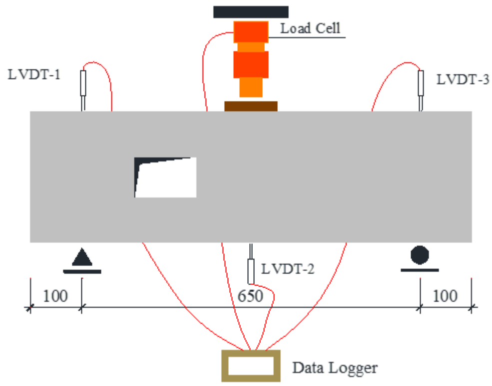


Figure 4. Test setup and instrumentation

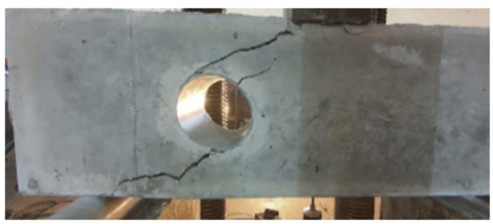
Figure 5. Image of a test in progress

3. Test result and discussion

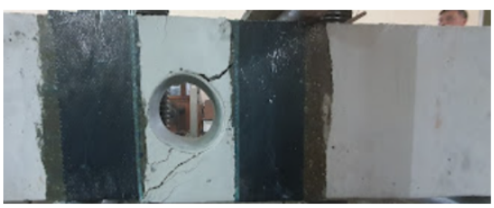
3.1. Overall behavior and failure mode

Fig. 6 presents the failure modes observed in all test specimens, with each specimen exhibiting shear mode failure. In the case of the control specimen, the crack originated at the support and propagated diagonally towards the loading point, forming an angle of approximately 45 degrees to the longitudinal axis of the beam. The crack patterns at failure for the two un-strengthened specimens, B1.1 and B2.1, are depicted in Figs. 6(b)–6(d). It is evident from these figures that both specimens failed due to the development of diagonal cracks in the top and bottom chords.

(a) Specimen B-0



(b) Specimen B-1.1



(c) Specimen B-1.2

(d) Specimen B-2.1

(e) Specimen B-2.2

(f) Specimen B-2.3

Figure 6. Failure modes of all test specimens

In the case of the B-2.3 specimen, which was strengthened on both sides of the opening as well as the top and bottom chords, failure was localized at the upper edge of the opening, resulting in the debonding of the CFRP sheets. The wrapping of the top and bottom chords prevented the formation of diagonal cracks in these regions. This outcome highlights the significant role of CFRP sheets in inhibiting crack development. Based on these results, it is indeed crucial to consider the arrangement of longitudinal and shear reinforcement in the top and bottom chords of RC beams with openings in the shear span. Proper reinforcement placement in these areas plays a significant role in enhancing the overall performance of the beams and preventing crack propagation.

3.2. Load-deflection relationship and the evaluation of strengthening effectiveness

Figs. 7, 8, and 9 present the relationship between applied load and deflection at the mid-span of the test specimens. These plots provide a visual representation of the structural response and deformation behavior of the beams under increasing loads. Table 4 provides a summary of the ultimate load, denoted as P_{max}, which represents the maximum load that the specimen can sustain before failure. It also includes the corresponding maximum shear resistance, denoted as V_{max}. These values are important indicators of the beam's capacity to resist shear forces. In addition, Table 4 presents the reduction in shear resistance observed in the two unstrengthened beams with openings in the shear span compared to the control beam B-0, which has no opening and is not strengthened. It also reports the gain in shear capacity achieved through the CFRP sheet strengthening relative to the corresponding unstrengthened specimens with openings.

Overall, the load-deflection plots and the corresponding values in Table 4 provide quantitative evidence of the effectiveness of the CFRP sheets in enhancing the shear resistance of the beams with openings, thereby validating the proposed strengthening approach.

Concerning the unstrengthened specimens, the findings from both Fig. 7 and Table 4 clearly illustrate the significant impact of openings on the shear capacity and behavior of the RC beams. The presence of openings in the beams leads to a notable reduction in beam stiffness, as evidenced by the increased deflection under applied loads. This reduction in stiffness directly affects the shear capacity of the beams. Furthermore, the results highlight that the shape of the opening influences the shear strength of the beams. Specifically, when comparing circular openings to rectangular openings with the same opening area, it is observed that

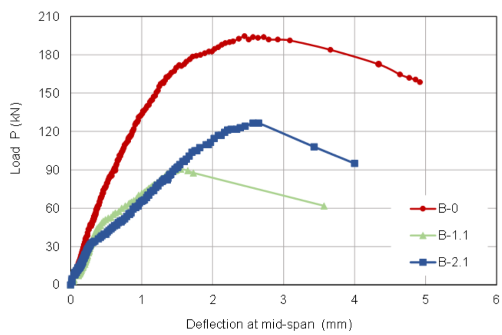


Figure 7. Load-deflection relationship of un-strengthened beams

Table 4. Test results

Test specimen	Ultimate load P_{max} (kN)	Shear resistance V_{max} (kN)	Reduction in shear resistance due to opening (%)	Gain in shear resistance due to CFRP (%)
Control beam				
B-0	192	96	0	0
Beams with opening, not strengthened				
B-1.1	90	45	57.3	-
B-2.1	127	64	29.1	-
Beams with opening strengthened				
B-1.2	97	49	-	7.8
B-2.2	138	69	-	7.8
B-2.3	133	67	-	4.7

[a] $V_{max} = P_{max}/2$

circular openings with a greater opening height result in a larger decrease in shear strength compared to beams with rectangular openings. This implies that the shape and dimensions of the openings have a significant influence on the shear capacity and overall structural behavior of the beams.

These findings emphasize the importance of considering the shape and dimensions of openings when evaluating the shear capacity of beams with openings. Circular openings with increased opening height should be carefully analyzed and accounted for in the design process, as they may have a more pronounced effect on the reduction of shear strength and overall structural response. Proper consideration of the opening shape and dimensions is crucial to ensure the desired level of shear capacity and structural performance in beams with openings.

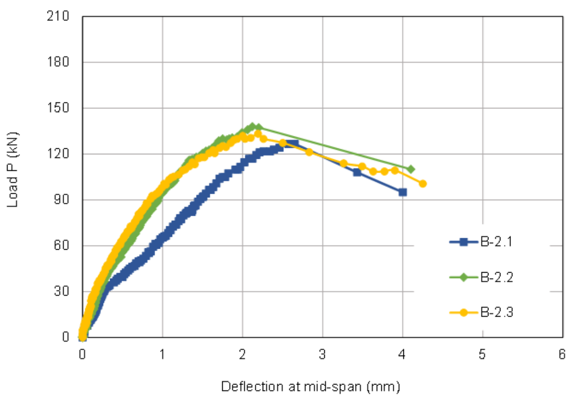


Figure 8. Load-deflection relationship of beams with a rectangular opening

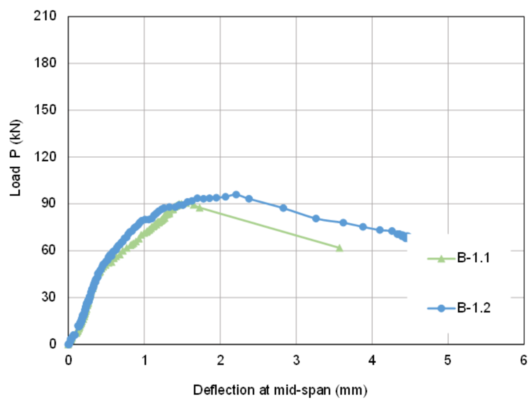


Figure 9. Load-deflection relationship of beams with the circular opening

Fig. 8 presents the load-deflection relationship of three RC beam specimens with rectangular openings, both strengthened and unstrengthened using CFRP sheets. Based on the results shown in Fig. 8, the effectiveness of CFRP sheet strengthening on the shear behavior of RC beams with rectangular openings can be evaluated. The results indicate that the application of CFRP sheets leads to an improvement in shear strength, although the increase may not be substantial in this specific study.

While the shear strength improvement may not be significant, it is important to note the increased stiffness exhibited by the strengthened beams B-2.2 and B-2.3. This heightened stiffness can be attributed to the participation of CFRP strengthening in bearing the shear force, thereby contributing to limiting the development of diagonal cracks caused by shear forces in RC beams. The stiffness enhancement suggests that the CFRP sheets contribute to enhancing the overall structural behavior of the beams with rectangular openings. The increased stiffness can contribute to a reduction in deflection, and improved structural integrity.

These findings are significant from the perspective of practical strengthening applications. Although the shear strength improvement may not be remarkable, the increased stiffness provided by CFRP materials can still offer valuable benefits in terms of structural performance. It indicates that CFRP sheets can effectively enhance the stiffness of RC beams with rectangular openings, thereby improving their overall behavior and resistance to deformation.

Regarding the behavior of the B-2.3 strengthened specimens, where CFRP sheets completely wrap the top and bottom chords, interesting insights are revealed. It is observed that the overall behavior and strengthening efficiency of B-2.3 are not significantly different from the B-2.1 specimen, which is only strengthened at the sides of the opening. This finding suggests that the complete wrapping of CFRP sheets on the chords does not contribute significantly to limiting shear failure in the presence of local cracks that originate at the corners of the opening.

The influence of local cracks on the failure behavior of the beam is substantial, indicating that specific crack patterns and failure mechanisms associated with openings play a critical role in the effectiveness of CFRP strengthening strategies. In the case of the B-2.3 specimen, the presence of local cracks originating at the opening corners appears to dominate the failure behavior, and the CFRP sheets on the chords do not effectively mitigate shear failure in this scenario.

Fig. 9 illustrates the load-deflection relationship of two beam specimens with circular openings, one with strengthening and one without. The results indicate that the shear strength and stiffness of the strengthened beam B-1.2 are not significantly improved compared to the unstrengthened beam B-1.1. This suggests that, for the circular opening size considered in this study, the approach of strengthening with CFRP sheets bonded on two sides of the circular opening is not effective in enhancing the shear capacity of the beam. It is important to note that the effectiveness of CFRP strengthening can be influenced by various factors, including the size and shape of the openings, as well as the specific application technique. In the case of circular openings, the bonding of CFRP sheets on two sides may not provide sufficient confinement or reinforcement to effectively mitigate shear failure. This indicates that alternative strengthening strategies or modifications to the CFRP sheet arrangement may be necessary for beams with circular openings. These findings highlight the importance of conducting a thorough analysis and considering the specific characteristics and failure mechanisms associated with circular openings when designing and implementing CFRP strengthening techniques.

4. Conclusions

The results of the above-mentioned research have improved the understanding of the behaviour of RC beams with a shear span to beam depth ratio (a/d) of 1.48, which is less than 2, and with openings, whether strengthened or unstrengthened with CFRP sheets, as well as the effectiveness of shear strengthening using CFRP sheets. Based on the results obtained in this study, the following conclusions can be drawn:

- For RC beams, the inclusion of openings in the shear span led to a significant decrease in both the shear strength and stiffness of the beams.

- It was observed that beams with circular openings, which have a greater opening height compared to beams with rectangular openings, exhibited a larger decrease in shear strength. This suggests that the geometry of the opening plays a significant role in determining the extent of shear strength reduction in beams with openings.

- The strengthening of openings with CFRP sheets bonded on two sides of the opening, as well as a complete wrap on the top and bottom chords, did not significantly enhance the shear strength of the beam. However, it was observed that this strengthening technique contributed to an increase in the stiffness of the beam.

It is worth noting that the specific findings of this study should be considered in the context of the experimental conditions and parameters investigated. The conclusions drawn from this research can provide valuable insights into the behavior of RC beams with openings and the potential benefits of using CFRP strengthening techniques. However, further studies and investigations are recommended to validate and expand upon these findings, considering different design configurations, opening sizes, and strengthening approaches.

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