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Shear Capacity of RC Beam with Opening Strengthened Using CFRP Sheet and Plate

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Abstract

This paper investigates the use of carbon fibre-reinforced polymer (CFRP) sheets and plates for the bi-directional reinforcement of reinforced concrete beams with transverse single and double symmetrical openings. The dimensions of the under-reinforced specimens are 1900mm in length, 150mm in width, and 300mm in height, with 3H12 tension reinforcement, 2H6 compression reinforcement, and R6-300 stirrups. This study aims to compare the maximal shear capacity of each CFRP configuration to that of conventional beams and evaluate the deflection profiles, failure modes, strain distribution, and crack patterns under shear loads. The beams are created using in-situ casting, and the openings are treated using post-drilling techniques to simulate real-world procedures. The beam specimens are subjected to a four-point stress test following the application of Sikadur-330 and CFRP. The principal findings indicate that the application of CFRP sheets increases the ultimate shear strength compared to conventional beams with openings, whereas the application of CFRP plates has the opposite effect. Nevertheless, the control beam with no openings has the greatest ultimate shear capacity. In addition, the sheet reinforced CFRP specimens exhibit less deflection than the control beam and conventional beams. The use of both CFRP sheets and plates aids in the transition from shear failure to flexural failure.

1. Introduction

Reinforced concrete (RC) beams play a crucial role in withstanding lateral loads in bending, shear, and torsion in various structural applications (Yassin, 2012; Pappachan, 2017). However, over time, steel and concrete structures are prone to deterioration, leading to potential failures (Kishore, Nasiry, & Rujhan, 2016). The design of RC beams must consider both ultimate and serviceability limit states. Optimal beam dimensions, such as span-to-depth ratios and width-to-depth ratios, are essential for achieving economical and efficient beam performance (Yassin, 2012). Additionally, sustainable practices and the need for building renovations have sparked the exploration of new materials, designs, and repair techniques for concrete structures (Bahrami, Ågren, & Kollberg, 2021; Pereira, Gaspar, Serrão, Mateus, & Silva, 2022). Carbon-fiber-reinforced plastic (CFRP) has emerged as a popular choice for reinforcing RC beams and enhancing their performance.

The installation of service ducts underneath RC beams is a common practice in modern construction, but it poses challenges for structural engineers in ensuring the beams' performance and durability (Ahmed & Gerges, 2020). Coring incidents, whether in new or old structures, can compromise the structural integrity and functionality of RC beams (Ahmed & Gerges, 2020). The process of coring may reduce the bonding strength between the concrete and reinforcement, leading to decreased shear and flexural capacity. It is important to develop coring techniques that minimize stress concentration points and diagonal fissures to maintain the long-term performance of RC beams. Strengthening existing beams with openings is also necessary to enhance their capabilities and prolong their service life (Mohammad & Al-Sulayfani, 2013). The use of CFRP reinforcements, such as CFRP laminates and sheets, has gained popularity, but further research is needed to compare their performance under different circumstances and optimize their application to beams with openings (Ahmed & Gerges, 2020; Alwash, Kadhum, & Mahdi, 2019; Li, Cheikhna Diagana, & Delmas, 2001; Al-Fatlawi & Hassan, 2016).

The objectives of this study are to investigate the shear capacity of simply supported RC beams with circular openings that are strengthened using CFRP sheet and plate. The study aims to analyse the deflection profile, failure modes, strain, and crack pattern of RC beams with openings that have been reinforced with CFRP sheet and plate under the influence of shear. Additionally, the study will consider various factors, such as the diameter and location of the opening, the location of applied load, the types of CFRP used and the method of CFRP strengthening. By providing proper reinforcement detailing around the prescribed openings, the study aims to minimize stress concentration and prevent premature failures.

2. Experimental Program and Strengthening Techniques

In the experimental program, all beam specimens were subjected to a 4-point load configuration with simply supported conditions. Prior to testing, the beams underwent a curing period of 28 days to ensure adequate strength development. The experimental setup consisted of two series of beam groups, both focused on studying the shear behaviour. The first series included conventional beams as the reference, as well as beams strengthened with CFRP sheets and CFRP plates, all of which had a single opening. The second series included the same configurations of conventional beams, CFRP sheet strengthening, and CFRP plate strengthening, but with beams featuring double-symmetrical openings. Each beam was progressively loaded until failure occurred.

2.1 Manufacturing of Beam Specimens

The beam specimens were cast with uniform dimensions, measuring 1900mm in length, 150mm in width, and 300mm in height. The design of the beams followed under-reinforced guidelines based on EC2, aiming to induce diagonal shear failure. The reinforcement scheme consisted of main tension reinforcement bars of 3H12, compression reinforcement of 2H6, and stirrups of R6-300. The clear concrete cover provided was 30mm. The reinforcement details and geometric arrangement can be seen in Figure 1. To enhance the structural integrity, both CFRP sheet and plate were employed as bi-directional strengthening materials according to the beam design, shown in Table 1, with the wrapping extending 100mm outward from the circumference of the opening. The curing period for all beams was 28 days to ensure sufficient strength development.

Table 1 *Design of RC Beam Specimens*

Beam Specimens	Number of Availability Circular Openings (100 mm)	Type od CFRP
B-C	-	-
BO-1	1	-
BO-2	2	-
BO-1-SCS	1	Sheet
BO-2-SCS	2	Sheet
BO-1-SCP	1	Plate
BO-2-SCP	2	Plate

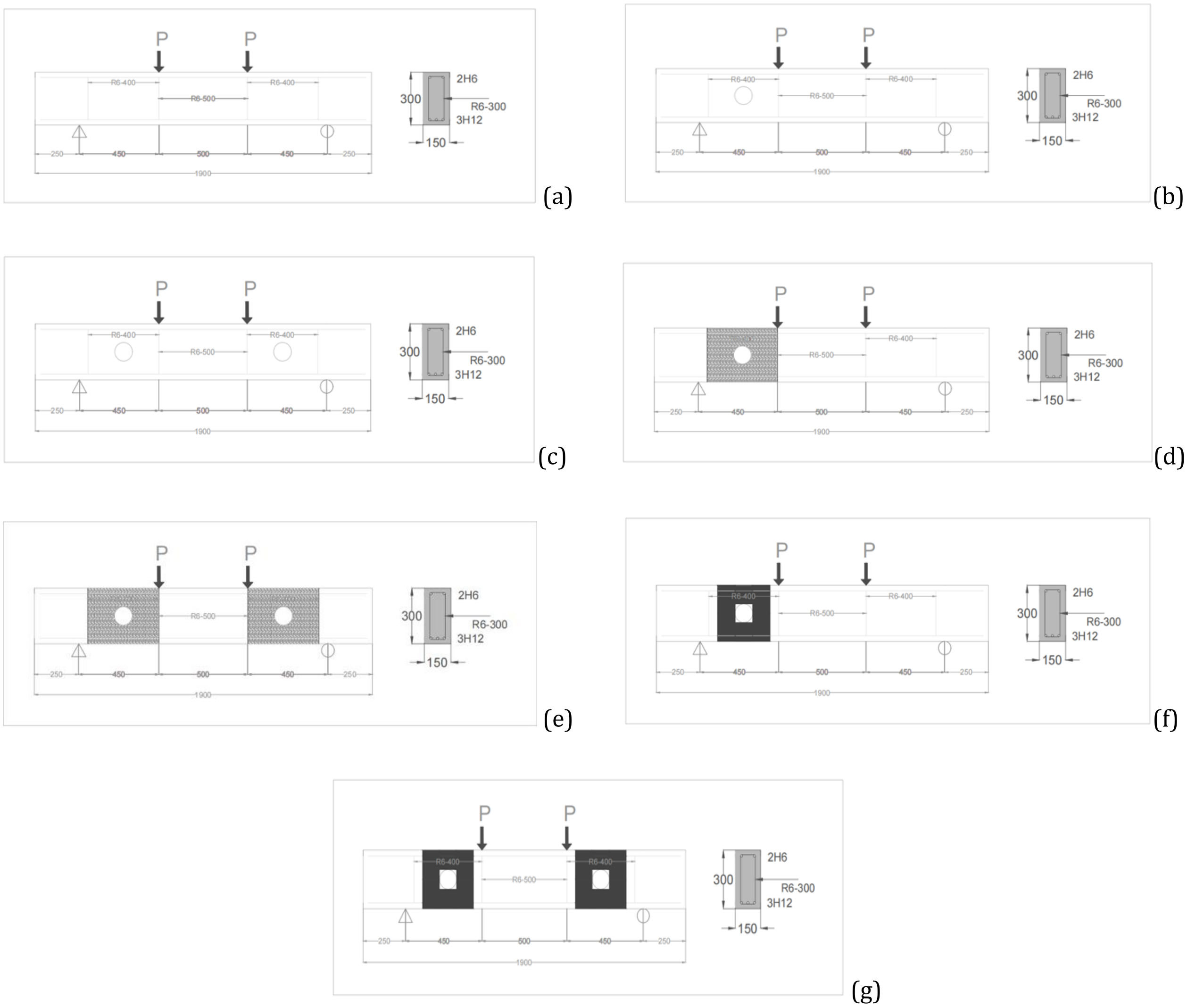


Fig. 1 *Design of RC Beam Specimens (a)- B-C; (b)- BO-1; (c)- BO-2; (d)- BO-1-SCS; (e)- BO-2-SCS; (f)- BO-1-SCP; (g)- BO-2-SCP*

All the beam specimens were subjected to the 4-point incremental load test method to evaluate their structural performance. The effective span of the beams was set at 1400mm. Point loads were precisely applied directly beneath the stirrups to ensure accurate loading conditions. The testing equipment employed a jacking machine with a static load capacity of 1000kN. To measure the maximum deflection of the beams, strain studies were conducted on the top mid surface of the beam specimens, as well as on the main reinforcement bars and stirrups. This was achieved using a Linearly Variable Differential Transducer (LVDT) for deflection measurements and strain gauges for strain analysis. Additionally, a load cell was utilized to obtain the load values. The test arrangements of the beam specimens are depicted in Figure 2, illustrating the positioning of the LVDT, strain gauges, and load cell.

3. Methodology

The methodology employed in this study involved several steps to ensure accurate and reliable results. Firstly, a concrete mix of grade C30 was used for the beam specimens, with the quality and desired compressive strength verified through slump tests and destructive cube tests. To measure the strain in the specimens, strain gauges were installed on the flattened surfaces of the stirrups and main bar reinforcement. Specifically, 4 strain gauges were affixed to 4 stirrups, while 6 strain gauges were attached to 2 main bars for each specimen. The proper functioning of the strain gauges was verified using a digital multimeter during the installation process. To obtain traverse coring specimens B4 to B7, a concrete horizontal borehole core drilling machine was utilized. Once the beams were completed, grid marks were applied at 50 mm intervals in both vertical and horizontal directions for labelling purposes. Subsequently, the CFRP plate and sheet were prepared and securely attached to the designated surfaces using epoxy at room temperature. The surfaces were roughened to ensure a strong bond between the external reinforcement and the surrounding area of the opening(s). The specimens were then allowed to harden for 7 days. Following the schedule, all beam specimens underwent the 4-point incremental load test method to assess their structural performance, shown in figure 2. The beams were subjected to point loads precisely positioned beneath the stirrups to ensure accurate loading conditions. The testing equipment employed a jacking machine with a static load capacity of 1000kN. To measure the maximum deflection of the beams, strain studies were conducted using strain gauges on the top mid-surface of the beam specimens, as well as on the main reinforcement bars and stirrups. Deflection measurements were obtained using a Linearly Variable Differential Transducer (LVDT), while strain analysis was conducted with the strain gauges. Additionally, a load cell was used to measure the applied load values.

Fig. 2 *4 Point Load Test of RC Beam Specimens*

4. Results and Discussion

4.1 Summarization Table Analysis

Table 2 summarizes key information related to the performance and behaviour of different beam specimens in the context of the project's objectives. The table provides a comprehensive analysis of important mechanical properties, such as the ultimate shear force, percentage difference, contribution of CFRP reinforcement, maximum deflection until fracture, percentage difference of deflection, modes of failure, and diagonal crack angles. These variables are crucial in evaluating the effectiveness of various beam designs in achieving the project's goal. The project aims to enhance the shear capacity and structural integrity of reinforced concrete (RC) beams using carbon fiber-reinforced polymer (CFRP) reinforcement. By examining the data presented in the table, one can assess the influence of factors such as openings and the type of CFRP reinforcement on the effectiveness of the beams.

Table 2 *An example of a table*

Beam Specimens	Ultimate Shear Force (kN)	Percentage Difference (%)	Contribution of CFRP Corresponds to the Corresponds Number of Opening	Max Deflection Until Fracture (mm)	Max Deflection Until Fracture (mm)
1- (B-C)	68.775	-	-	35	-
2- (BO-1)	64.344	6.44	-	46.95	34.14
3- (BO-2)	51.271	25.45	-	53.2	52
4- (BO-1-SCS)	66.452	3.38	3.28	24.9	-28.86
5- (BO-2-SCS)	56.758	17.47	10.7	26.05	-25.57
6- (BO-1-SCP)	56.536	17.8	-12.13	56.55	61.57
7- (BO-2-SCP)	41.958	38.99	-18.16	29.95	-14.43

Beam Specimens	Modes of Failure	Diagonal Crack Angle
1- (B-C)	shear compression failure , shear plug exists, flexural cracking	37 ° on top, 24° incline at support
2- (BO-1)	shear compression failure , shear plug exists, flexural cracking	24° at the point load, 23° at the support zone
3- (BO-2)	major shear tension failure , shear plug exists, flexural cracking	29° at the point load,37° at the support zone
4- (BO-1-SCS)	major flexural failure, debonding and rupture of CFRP sheet at the compression zone	invisible
5- (BO-2-SCS)	minor tension shear failure, major flexural failure, debonding and rupture of CFRP sheet at the compression zone	85° at the top, 63° at the bottom
6- (BO-1-SCP)	major compression failure, flexural cracking, debonding of CFRP plate	41° at the top, 61° at the support
7- (BO-2-SCP)	major compression failure, flexural cracking, debonding of CFRP plate	30°at the top, 53°at the support

4.2 Shear Deflection Analysis

In the experimental investigation conducted, the behaviour of the beam specimens under different configurations and the influence of CFRP reinforcement were examined. The results obtained from the load-deflection curves indicated distinct variations in the structural performance of the beams as shown in Figure 3. The controlled beam (Beam Specimen 1) initially exhibited linear elastic behaviour but displayed non-linear characteristics with the development of cracks as the load increased. Beam Specimens 2 and 3, with one and two symmetric openings respectively, demonstrated significant decreases in ultimate shear force compared to the control beam. The incorporation of CFRP reinforcement in Beam Specimens 4 and 5 resulted in slightly increased or decreased ultimate shear forces, while the maximal deflection before fracture varied compared to the control beam. The findings were consistent with previous studies that reported enhancements in load-bearing capacity with the use of CFRP reinforcement, up to a certain quantity of CFRP sheets employed. The results also indicated that the addition of CFRP plates had differing effects on the ultimate shear force and maximal deflection of the beams, with reductions observed in both parameters for Beam Specimen 7.

These findings align with previous research conducted by (Adsam et al., 1996), who investigated the retrofitting of RC structural beams using CFRC and observed an increase in maximum load capacity and rigidity. (Shah et al., 2020) also reported significant improvements in the concentrated load capacity of CFRP-reinforced and strengthened beam specimens compared to control beams. The experimental results obtained in this study confirm the impact of CFRP reinforcement on the structural behaviour of beams, providing further support for the use of CFRP in retrofitting applications.

The load-deflection curves of the strengthened beams (Beam Specimens 6 and 7) exhibited different trends compared to the control beam. Beam Specimen 6, with one opening and CFRP plate reinforcement, displayed a slight increase in ultimate shear force but a significant increase in maximal deflection before fracture compared to the control beam. On the other hand, Beam Specimen 7, with two openings and CFRP plate reinforcement, exhibited the lowest ultimate shear force and a decreased maximal deflection before failure compared to the control beam. These results indicate the varying effects of CFRP plate reinforcement on the structural performance of the beams, with the number and arrangement of openings influencing the ultimate shear force and deflection characteristics.

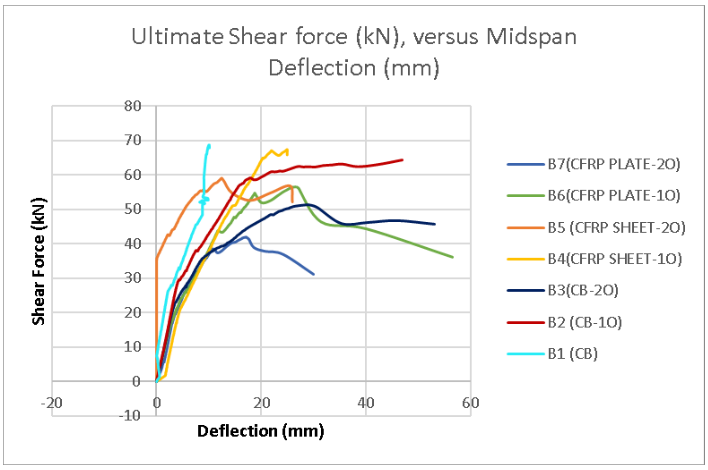


Fig. 3 *Ultimate Shear force (kN), versus Midspan Deflection (mm)of 7 Studied Beam Specimen*

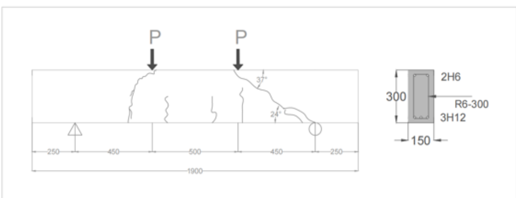
4.3 Failure Mode Analysis

In the analysis of the failure modes of the RC beam specimens shown in figure 4, several key observations were made for each specimen. Specimen B1 (B-C) exhibited flexural cracking at a load of 50.663 kN, followed by shear cracking at 41.65 kN and diagonal shear cracking at 53.99 kN. The failure mode was characterized by diagonal shear failure within the stirrup arrangement boundary, indicating the importance of shear reinforcement (Kumar, Siva Chidambaram, & Agarwal, 2016). Specimen B2 (BO-1) showed similar cracking patterns, with flexural and shear cracking at 49.476 kN and diagonal shear cracking at 39.144 kN. Notably, X-shaped cracks were observed at the outside boundary of the opening. Specimen B3 (BO-2) displayed flexural cracking at 30.494 kN and shear cracking at 34.049 kN, with a biased one-sided failure mode in shear within the stirrup arrangement along the opening. X-shaped cracks were also observed outside the opening.

In the case of specimen B4 (BO-1-SCS), the failure mode indicated shear-flexural failure, with flexural cracking at 30.04 kN and a combination of flexural and shear cracking at 28.49 kN. The presence of CFRP sheet reinforcement was observed, but with some debonding at the point load area. For specimen B5 (BO-2-SCS), flexural cracking was observed at 25.456 kN, followed by shear cracking at 30.192 kN. The failure profile exhibited one-sided bias and debonding of the CFRP sheet in the region of the point load.

Specimen B6 (BO-1-SCP) showed flexural cracking at 24.05 kN and shear cracking under the point load side with the opening and CFRP plate strengthening. Another shear cracking was observed on the opposite side of the point load. The failure profile indicated diagonal shear cracks and debonding of the CFRP plate along the shear diagonal line. Specimen B7 (BO-2-SCP) exhibited flexural cracking at 25.53 kN and transverse coring shear cracking and widening at 40.478 kN. The failure mode was characterized by a biased one-sided failure with inclined shear cracks and no debonding observed.

From B4 to B7, under the CFRP reinforcement, bonded using Sikasdure-300, was found to improve the shear capacity of the RC beam specimens by effectively resisting shear forces and enhancing structural performance (Grace, Singh, Shinouda, & Mathew, 2005).



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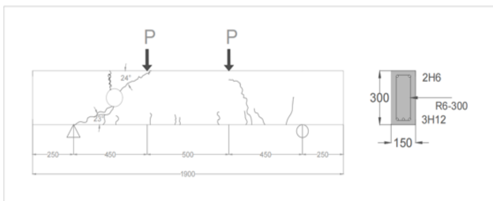

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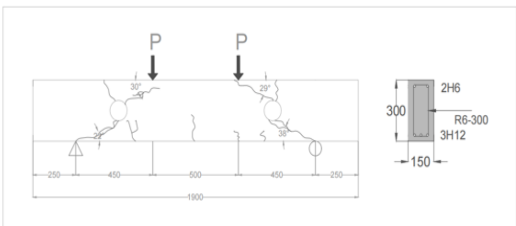

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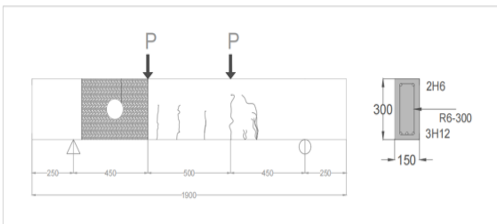

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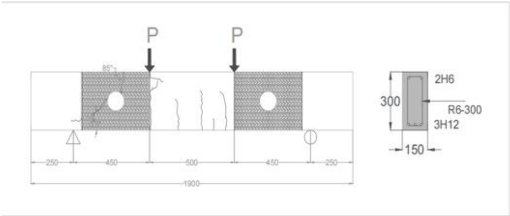

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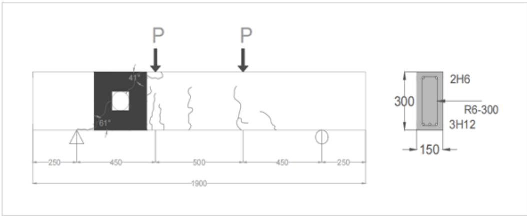

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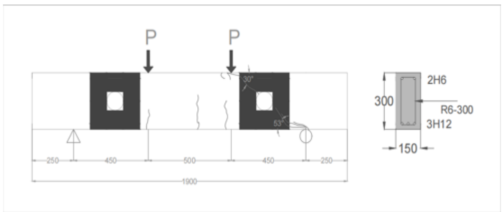
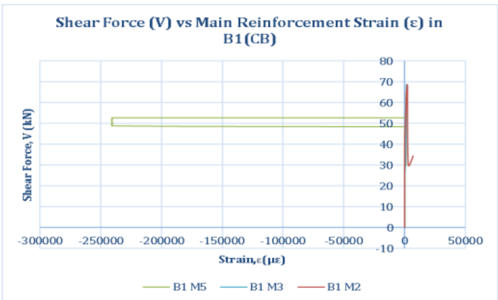


(g)

Fig. 4 *Failure Analysis of RC Beam Specimens (a)- B-C; (b)- BO-1; (c)- BO-2; (d)- BO-1-SCS; (e)- BO-2-SCS; (f)- BO-1-SCP; (g)- BO-2-SCP*

4.4 Shear- Strain Analysis in Main Reinforcement

The stress-strain relationship of the primary reinforcement bars in the seven RC specimens (Figure 5) subjected to a four-point axial load test provides crucial insights into the tensional behaviour of the beams. In the control beam (B1), shear cracking occurs abruptly, surpassing the allowable limits, and deformation in the shear zone is evident despite the plastic deformation of the steel bar. This phenomenon can be attributed to the shear deficiency resulting from large stirrup spacing, as noted by (Kumar, Siva Chidambaram, & Agarwal, 2016). Analysing the strain curves reveals that the longest strain values correspond to the zones of maximum flexural cracking and fracture caused by tensile stresses. The strain gauges located at the shear failure zones in B1 exhibit the highest strain values. In beams with circular openings (B2, B4), the strain gauges associated with the openings display the greatest strains, while in beams with two symmetrical circular openings (B3, B5), the strain gauges at the flexural zones in the centre exhibit significant strain values. The strain distribution analysis helps understand the impact of openings and CFRP reinforcement on the stress-strain behaviour of RC specimens, particularly in the tensional portion of the main reinforcement.



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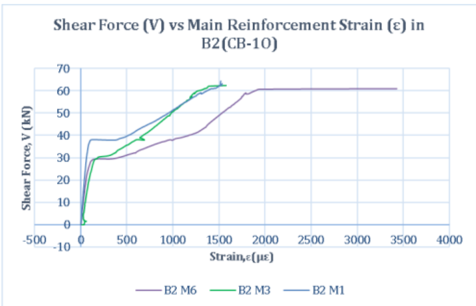

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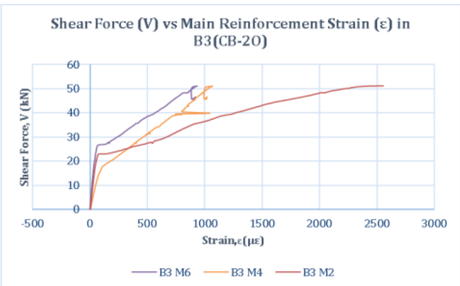

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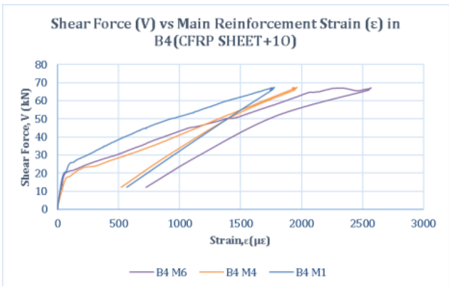

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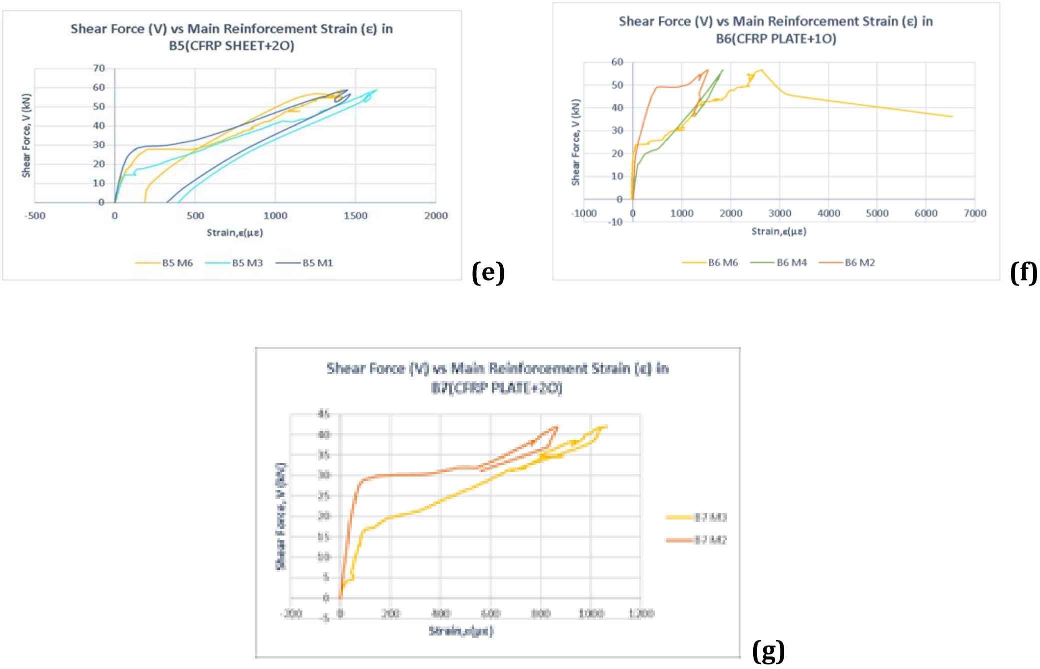

Fig. 5 *The Shear-Strain Graph Along the Main Reinforcement Bar (a)- B-C; (b)- BO-1; (c)- BO-2; (d)- BO-1-SCS; (e)- BO-2-SCS; (f)- BO-1-SCP; (g)- BO-2-SCP*

4.5 Shear- Strain Analysis in Stirrup

The stress-strain diagrams obtained from the four-point axial load test conducted on the seven RC specimens (see Figure 6) reveal distinct patterns and behaviours in the stirrups. The control beam specimen (B1) exhibits positive yielding until a load of 48.65 kN, indicating tension forces in the stirrup. In the case of the RC beam with a single opening (B2), the presence of the opening induces compression yielding in the stirrup, resulting in negative strain values. Similarly, the RC beam with two symmetrical openings (B3) demonstrates compression yielding in the stirrup, but with a greater negative strain value than B2. In B4, where a single-opening beam is strengthened with a CFRP sheet, the tension characteristics of the stirrup are restored. B5, with two symmetrical openings and CFRP sheet reinforcement, exhibits tension yielding in the stirrup. B6, with CFRP plate reinforcement on a single-opening beam, shows an elastic compression region in the stirrup until a certain shear load, followed by strain-hardening. Finally, B7, with two symmetrical openings and CFRP plate reinforcement, reaches yield strength and maximum shear strength in the stirrup before fracture occurs. The presence of CFRP reinforcements increases compressive resistance and strain capacity in the corresponding specimens.

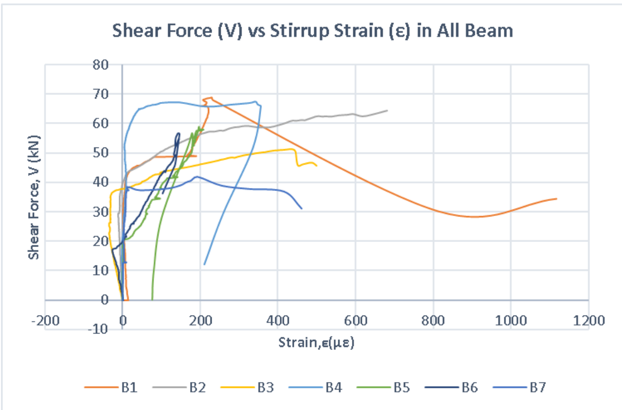

Fig. 6 *The Shear-Strain Graph in Each Stirrup of All Beam Specimens (B1 to B7)*

4.6 Shear- Strain Analysis on Top Midspan Concrete

The stress-strain diagrams obtained from the 4-point axial load test conducted on the seven RC specimens presented notable patterns and correlations (see Figure 7). The strain measurement taken from the flat surface at the top mid-span of the specimens revealed a compression zone indicated by negative strain values. A cluster comprising B1, B2, B3, and B5 exhibited similar yielding angle patterns. Among the specimens, B7 displayed the most gradual slope, while B6 had the least steep curve, suggesting that multiple openings contribute to enhanced compressive reinforcement facilitated by the CFRP plate. These empirical findings support the claim that a beam with two symmetrical openings (B7) provides greater compressive reinforcement than the reference beam (B1), B2, and B3 but falls short of B6, which incorporates a single opening reinforced with CFRP. Furthermore, the compressive reinforcement offered by a CFRP sheet weakens as the number of openings increases. B4, featuring a single opening and a CFRP layer, exhibited superior compressive reinforcement compared to B1, B2, and B3. However, when considering beams with two symmetrical openings, the inclination angle tended to align with that of B1, B2, and B3.

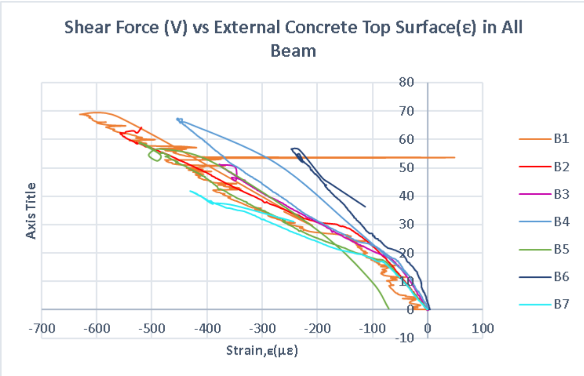

Fig. 7 *The Shear-Strain Graph on The Concrete Surface at The Mid-span of All Beam Specimens (B1 to B7)*

5. Conclusions

This study has investigated the shear capacity of RC beam with opening strengthened using CFRP sheet and plate. Throughout the study, key conclusions can be summarized as follows:

i. The presence of 100 mm diameter circular openings in the beams led to a decrease in beam stiffness and shear compression performance. The areas around the openings acted as shear stress concentration zones, resulting in diverging shear distribution lines.

ii. The shear capacity recovery rate varied among the different beam specimens. The control beam exhibited the highest ultimate shear force, followed by the other beams, with percentage differences ranging from 6.44% to 38.99%.

iii. Comparing the effectiveness of CFRP plate and sheet reinforcements, it was observed that the CFRP sheet had greater stiffness and contributed positively to shear restoration in beams with one or two symmetrical openings. The CFRP plate, on the other hand, tended to decrease overall shear performance in beams with openings.

iv. The failure modes, crack patterns, and stress-strain behaviour varied across the specimens, with different failure modes observed in different beams. The CFRP sheet exhibited major flexural failure and minor tension failure, while the CFRP plate showed major compression shear failure.

v. The application of CFRP sheet and plate reinforcements resulted in less deflection compared to beams without reinforcement. The CFRP sheet exhibited slightly more deflection in beams with one opening, while both reinforcements showed less deflection compared to the beam with two openings without reinforcement and the control beam.

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