

Comparative Analysis of High-Strength Concrete Cylinders Reinforced with Varied Configurations of Carbon Fibre Reinforced Polymer Strips

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Abstract

Concrete, a material renowned for its robustness, flexibility, and cost-efficiency, is ubiquitously employed in a multitude of structural applications. Among its variants, High Strength Concrete (HSC), characterized by a compressive strength exceeding 40 MPa, has emerged as a focal point of interest in contemporary structural engineering research. The incorporation of Carbon Fibre Reinforced Polymer (CFRP), a high-strength composite material, as a strengthening agent in HSC structures represents a novel approach in the field. This study embarks on a comprehensive investigation to assess the efficacy of different configurations of CFRP strips in augmenting the strength of HSC cylinders. A total of fifteen HSC cylinders, each reinforced with a unique configuration of CFRP strips, were subjected to rigorous testing. The cylinders, cast using a standard mould, measured 150 mm in diameter and 300 mm in length. The experimental results revealed a significant enhancement in the strength of the CFRP-reinforced cylinders. Notably, cylinders reinforced with horizontal CFRP strips exhibited an increase in strength of approximately 68% compared to the unconfined specimens. This substantial increase underscores the potential of horizontal CFRP strip configuration in optimizing the strength of HSC structures. Moreover, an analysis of the stress-strain behavior of the CFRP-reinforced cylinders yielded insightful findings. Both the stress and strain behaviors of the CFRP-reinforced cylinders, irrespective of the CFRP strip configuration, surpassed those of the unconfined specimens. This observation affirms the role of CFRP strips in not only enhancing the strength but also improving the overall mechanical performance of HSC cylinders. In conclusion, the findings of this study unequivocally demonstrate that CFRP strips significantly enhance the strength of HSC cylinders. The results underscore the potential of CFRP strips, particularly in horizontal configuration, for widespread application in structural engineering, paving the way for more resilient and efficient concrete structures. Future research could explore the impact of varying the thickness and material properties of

the CFRP strips to further optimize the performance of HSC structures.

1. Introduction

High Strength Concrete (HSC) stands at the forefront of modern structural engineering, offering unparalleled strength and durability to withstand the rigors of contemporary construction demands. With a compressive strength surpassing 40 MPa, HSC represents a formidable material choice for a wide array of applications, ranging from high-rise buildings to infrastructure projects [1]. The inherent robustness and versatility of concrete have long made it a cornerstone of construction, providing engineers with a reliable medium for shaping the built environment [2]. However, as structural requirements evolve and design parameters become increasingly stringent, the pursuit of materials capable of delivering enhanced performance characteristics become imperative.

In response to these evolving demands, the integration of advanced reinforcing materials has emerged as a pivotal strategy for optimizing the performance of concrete structures. Among these materials, Carbon Fibre Reinforced Polymer (CFRP) stands out for its exceptional mechanical properties and versatility in application [3]. Comprising high-strength carbon fibres embedded in a polymer matrix, CFRP offers a unique combination of lightweight construction, corrosion resistance, and high tensile strength, making it an ideal candidate for enhancing the performance of concrete elements [4].

The application of CFRP in HSC structures represents a convergence of cutting-edge materials science and structural engineering principles, unlocking new possibilities for performance enhancement and structural optimization. By strategically integrating CFRP reinforcement, engineers can tailor the mechanical properties of concrete structures to meet specific design requirements, whether it be increasing load-bearing capacity, improving durability, or enhancing seismic resistance [5], [6]. Moreover, the versatility of CFRP allows for the customization of reinforcement configurations, offering engineers a nuanced toolkit for addressing diverse structural challenges.

While previous research has explored the efficacy of CFRP reinforcement in various structural elements, including columns, beams, and slabs, a comprehensive comparative analysis of different CFRP configurations in HSC cylinders remains a fertile area for investigation. The cylindrical form factor presents unique challenges and opportunities for reinforcement, necessitating a detailed examination of CFRP strip layouts, confinement schemes, and anchorage techniques [7], [8]. By systematically evaluating the performance of HSC cylinders reinforced with different CFRP configurations, this study aims to explain the underlying mechanisms governing strength enhancement and mechanical behaviour.

2. Research Methodology

The procedure of conducting experimental work can be represented graphically in the flowchart illustrated in Fig. 1. This flowchart presents a sequential process for evaluating the compressive strength of HSC. The process commences with the formulation of the design mix and the selection of aggregates. This is then followed by the batching of materials, conducting a slump test, and casting concrete cylinders. The flowchart provides a comprehensive overview of both the unconfined and confined steps that precede the final compressive strength tests. The HSC undergoes different configurations - vertical, horizontal, inclined - during the unconfined tests to assess its response in different orientations.

This investigation primarily focuses on the strip CFRP, the fully confined CFRP, and the control cylinder specimen without CFRP. The secondary parameters consist of three separate configurations of the strip CFRP, specifically vertical, inclined, and horizontal. The purpose of evaluating these configurations was to determine which one offers the highest level of strength for HSC. Fig. 2 displays a collection of cylinder specimens used in the study to evaluate the strength of HSC when reinforced with CFRP in different arrangements. The figure is divided into five subsections, labelled (a) to (e), each illustrating a distinct experimental setup or stage. Fig. 2 (a) contains three control cylinder specimens that do not have CFRP. The specimens, which consist entirely of concrete, are used as a benchmark for comparison with the specimens reinforced with CFRP. Fig. 2 (b) depicts three completely enclosed cylinders made of CFRP. The concrete in these samples is completely covered by CFRP, resulting in a dark and textured surface due to the presence of carbon fibre. This configuration is used to measure the effect of complete confinement on the strength of HSC. Fig. 2 (c) presents the strip CFRP configurations applied to three cylinders. Nevertheless, the precise configurations - whether they are vertical, inclined, or horizontal - cannot be determined because of the angle of the photograph. These configurations are used to assess the impact of partial confinement on the strength of HSC. Fig. (d) introduces three cylinders with strip CFRP configurations that are positioned further apart, suggesting a potentially distinct arrangement compared to the ones in Fig. (c). Fig. 2 (e) showcases an alternative arrangement of strip CFRP configurations on three cylinders, where the strips are visibly separated, differentiating it from Fig. 2 (c) and Fig. 2 (d). Each of these configurations is carefully examined to determine which one provides the greatest level of durability to

HSC. The CFRP strips are arranged in a configuration where each strip has a width of 50 mm and is spaced 20 mm apart. The CFRP strips overlap by 50 mm in length, except for the vertical arrangement. The CFRP arrangement is positioned at an inclination of 18 degrees.

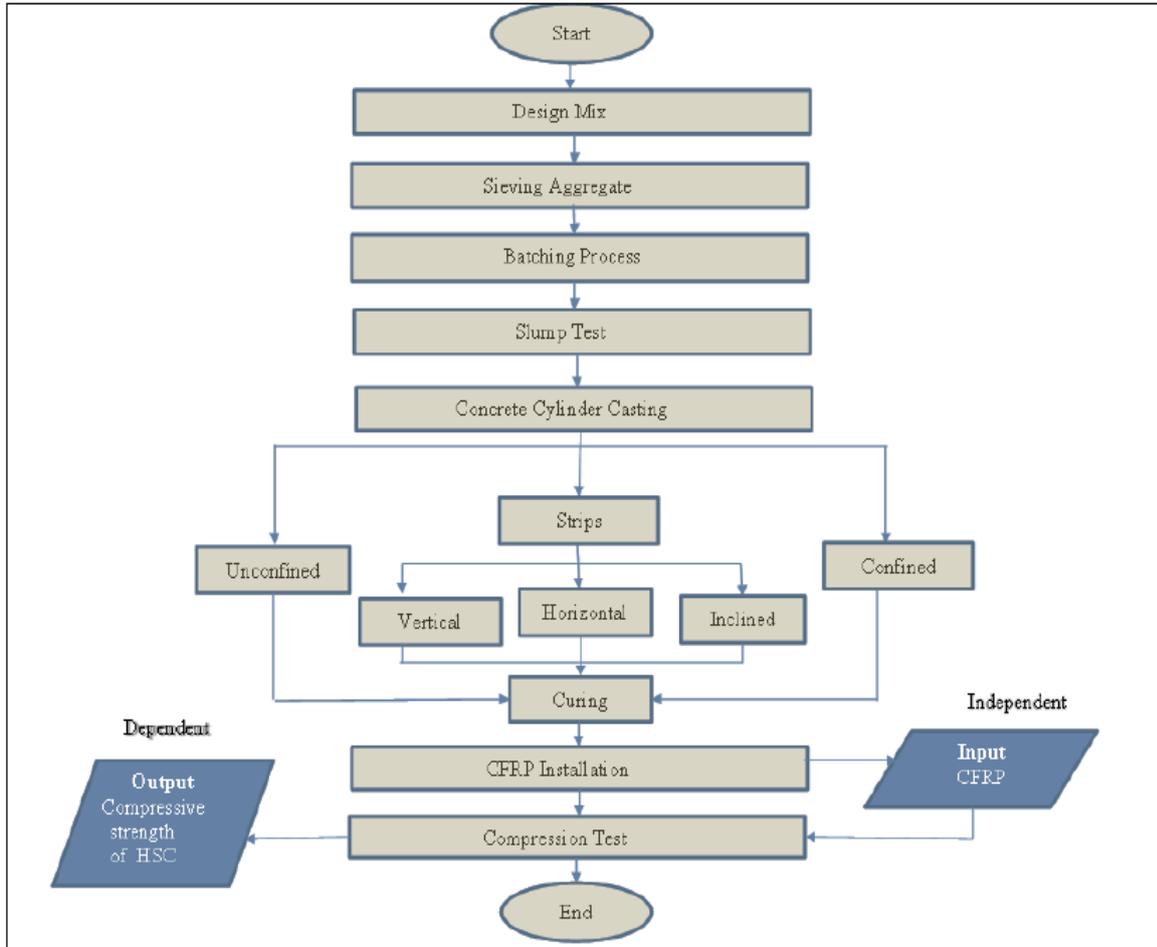


Fig. 1 Flowchart for the experimental work

The specimens used in the strip configuration incorporated CFRP with a width of 50 mm and a spacing of 20 mm. A 50 mm overlap in the length of CFRP is considered, with the exception of the vertical arrangement. The CFRP arrangement is set at an angle of 18°. In this study, the design mix table for M50 concrete was used. The table was developed based on the Concrete Mix Design form method of the Building Research Establishment (BRE). This design mix form simplifies the implementation of the mixing procedure. The amounts of cement, water, fine aggregate, and coarse aggregate needed for a cylinder mould measuring 150 mm × 300 mm will be multiplied by a factor of 15 to accommodate the number of specimens needed for this study.

Sieve analysis, also referred to as the gradation test, is an essential prerequisite for all technicians working with aggregates. The purpose of this assessment is to evaluate the distribution of aggregate particles by size in a particular sample. This is done to ensure that the sample meets the requirements and specifications for design, production control, and verification. Sieves are required to adhere to the specifications outlined in the AASHTO M92 standards. When using a mechanical sieve shaker, it is important that the sieve moves in both vertical and lateral directions. This movement causes the particles to bounce and rotate, which results in different orientations of the particles on the sieving surface. Nevertheless, as a result of limitations in laboratory equipment, the process of sieving was carried out by hand. The largest cumulative size achieved was 20 mm, followed by 10 mm. The sieve sizes employed in the procedure were 28 mm, 20 mm, 14 mm, and 10 mm, and the aggregate sizes were chosen from within this range.

The process of batching involves measuring the quantity or proportion of components, such as cement, aggregates, water, etc., to create the concrete mix. Effective batching improves the workability of concrete by minimising segregation or bleeding. After finishing the batching process, the preparation of CFRP began. The confined CFRP has dimensions of 471.3 mm in length and 300 mm in height. A 50 mm overlap is incorporated into the CFRP to eliminate any adhesive bubbles and improve the bond between the concrete cylinder and the

CFRP. Each of the three samples contained 12 strips of CFRP arranged horizontally, with each strip measuring 50 mm in width. Ultimately, the cylinder mould was readied through the process of cleansing, eliminating any particles, and reshaping, while the screws were securely fastened using spanners measuring 19 mm and 21 mm in size. Subsequently, the cylinder was lubricated with oil to enhance the ease of remoulding between the cylinder specimen and the mould.

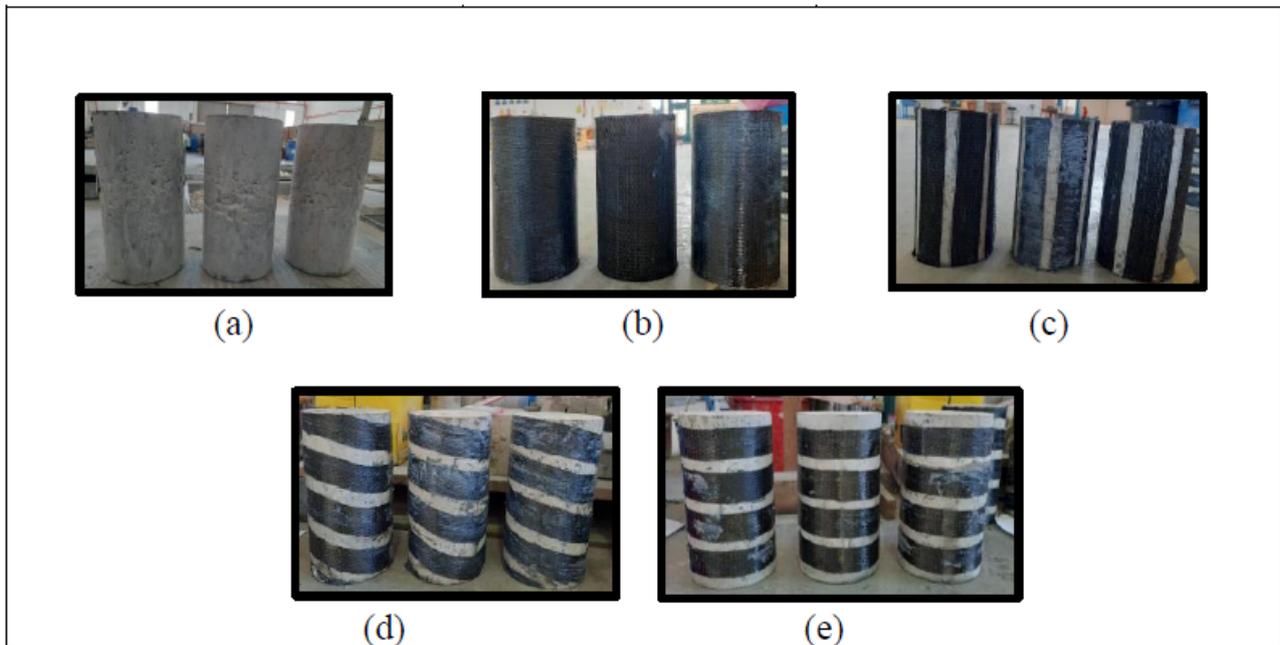


Fig. 2 The sample of concrete cylinder specimen with various CFRP confinement techniques

3. Results and Discussion

The results and discussion offer an explanation for each finding. The justification is being made to ensure the reliability of the results in relation to the objectives that were set at the beginning of the research study. In this study, the compressive strength, deformation, and strain were determined based on the collected data. The results were utilized to compare the optimal configuration of CFRP strips for an HSC concrete cylinder. The focus of the failure mechanism has been on the crack pattern of the cylinder specimen. Prior to this, the study of structural behaviour primarily concentrated on load-deformation and stress-strain characteristics.

3.1 Crack Pattern

According to the results of this study, the cylinder specimen exhibited various crack patterns when subjected to compression with an axial force, as depicted in Fig. 3. Fig. 3 depicts a graphical illustration of five different crack patterns that were detected in cylindrical specimens when subjected to axial compression force. The patterns are classified as unconfined (a), confined (b), vertical (c), inclined (d), and horizontal (e). Every category exhibits distinct fracture features, which contribute to a thorough comprehension of the behaviour of cylindrical specimens under various situations and restrictions. Table 1 enhances the information presented in Fig. 3 by offering a comprehensive overview of the crack patterns and failure modes seen in different types of cylindrical specimens. The specimens are labelled as V for vertical, H for horizontal, I for inclined, and U for unconfined. The table establishes a correlation between each specimen type and its observed crack pattern and categorizes the fracture type based on ASTM C39 standards.

The crack patterns for unconfined, confined, vertical, inclined, and horizontal conditions were represented as (a), (b), (c), (d), and (e), respectively. Several types of fractures could be analyzed based on the compression result. The fractures were classified as Type 2, 3, 5, and 6. The variation in the fracture pattern arises due to the inclusion of CFRP strips and the magnitude of the compressive stress exerted on the cylinder specimen. The typical crack pattern observed in cylinder specimens is conical in shape, although it may exhibit variations based on the quality of the specimen fabrication and the type of reinforcing material employed.

Upon analyzing Table 1, numerous significant discoveries emerge. Specimens V_1 and U_1 displayed a columnar crack pattern distinguished by vertical cracks extending through both ends without well-defined cones, categorized as Type 3 fractures. Specimens V_3, H_1, H_2, H_3, and I_3 exhibited Type 2 fractures, characterised by the absence of a distinct cone shape on one end and the presence of vertical cracks across the caps. Specimen I_1 is distinguished by its pointed cylinder end and is classified as a Type 5 fracture. Specimen I_2 underwent a side fracture either at the top or bottom, which was classified as a Type 6 fracture.

The variation in the fracture patterns can be related to the presence of CFRP strips and the level of compression force exerted on the cylindrical specimens. The typical crack pattern observed in cylindrical specimens is conical in shape, although it may differ based on the quality of specimen production and the type of reinforcing material employed. This analysis offers significant insights into the behaviour of cylindrical specimens when subjected to compressive loads, as well as the impact of parameters such as confinement, orientation, and strengthening material on crack patterns and failure modes. It enhances comprehension of the material's response to stress, which is vital for the design and analysis of structures. This work emphasizes the need for meticulous observation and categorization of crack patterns in comprehending the intricate behaviour of materials when subjected to stress. Furthermore, it emphasizes the possibility of utilizing CFRP strips and adjusting compression loads to control and forecast the failure mechanisms of cylindrical specimens.

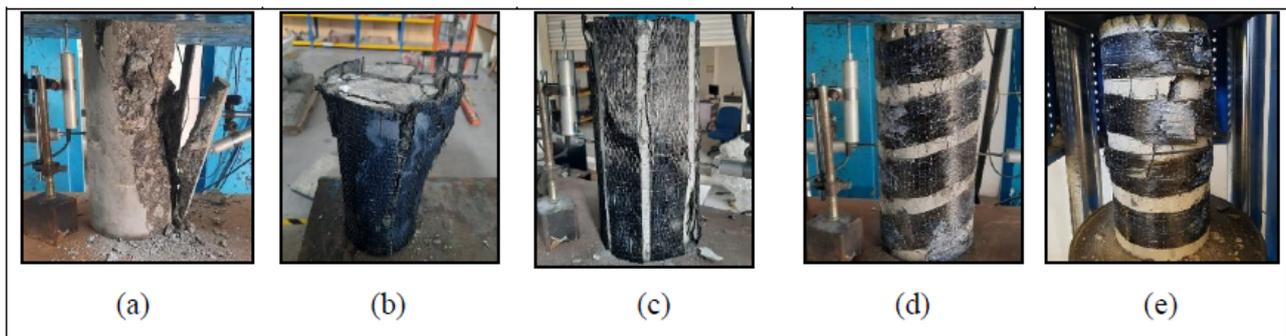


Fig. 3 The crack pattern of cylinder specimen; (a) UC (b) C (c) V (d) I (e) H

Table 1 Summary crack pattern and failure mode of cylinder specimen

Type of Specimen	Crack Pattern	Type of fracture by ASTM C39
V_1	Columnar	Type 3
V_2	Columnar	Type 3
V_3	No well-defined cone on other end	Type 2
H_1	No well-defined cone on other end	Type 2
H_2	No well-defined cone on other end	Type 2
H_3	No well-defined cone on other end	Type 2
I_1	End of cylinder is pointed	Type 6
I_2	Side fracture at top or bottom	Type 5
I_3	No well-defined cone on other end	Type 2
U_1	Columnar	Type 3
U_2	Columnar	Type 3
C_1	Columnar	Type 3
C_2	Side fracture at top or bottom	Type 5
C_3	Side fracture at top or bottom	Type 5

3.2 Load-Displacement

The maximum load applied for both horizontal and vertical deformation. The cylindrical specimens underwent a consistent load, with a maximum of 1000 kN applied using a reaction frame machine and up to 2000 kN applied during a compression test. Utilizing several types of machinery led to minor variations in the load-displacement outcomes. The Linear Variable Differential Transformer (LVDT) was used to quantify horizontal displacement on both the left and right sides. Thus, the graph alone depicted the highest extent of lateral displacement of the cylindrical specimen.

Fig. 4 presents a comprehensive representation of the load-deformation characteristics of the cylindrical specimens. The data set consists of two graphs: (a) Load vs Horizontal Deformation and (b) Load vs Vertical Deformation. The graphs provide a comparative investigation of the deformation characteristics of unconfined, horizontally oriented CFRP strip and inclined CFRP strip cylindrical specimens under different loads.

According to Fig. 4 (a), the unconfined specimen was subjected to a load of 397.3 kN, which caused horizontal and vertical deformations of 14.986 mm and 8.9315 mm, respectively. Notably, the horizontal CFRP strip cylindrical specimen saw the maximum load, measuring 764.2 kN. Although the load was greater, the horizontal and vertical deformations were considerably reduced, measuring 0.970 mm and 3.093 mm, respectively. These findings indicate that the cylindrical specimen with a horizontal CFRP strip showed better structural integrity and resilience when compared to the unconfined specimen.

Fig. 4 (b) provides additional evidence to support these findings by displaying the vertical deformations under comparable loading circumstances. The unconfined specimen exhibited a vertical displacement of 8.9315 mm under a load of 397.3 kN, suggesting its vulnerability to vertical stresses. Conversely, the horizontal CFRP strip specimen demonstrated structural stability even under high loads, reaching a maximum load of 764.2 kN while only experiencing a vertical displacement of 3.093 mm. The inclined CFRP strip specimen had the second-highest load, measuring 616.5 kN. It exhibited horizontal and vertical deformations of 0.503 mm and 3.623 mm, respectively. This suggests that the CFRP strip specimen, when inclined, also showed significant resistance when subjected to high loads.

The findings depicted in Fig. 4 offer a significant understanding of the deformation characteristics of cylindrical specimens subjected to different loads. The impact of the horizontally oriented CFRP strip on the load-bearing capacity of the cylindrical specimens is apparent, leading to a significant delay in the occurrence of failure. Although the unconfined specimen fails at a slower rate, the horizontal CFRP strip cylindrical specimen can withstand a greater weight, highlighting the efficacy of CFRP strips in improving the structural integrity of cylindrical specimens. These findings make a substantial contribution to the comprehension of how materials behave when subjected to stress, which is essential for the design and analysis of structures.

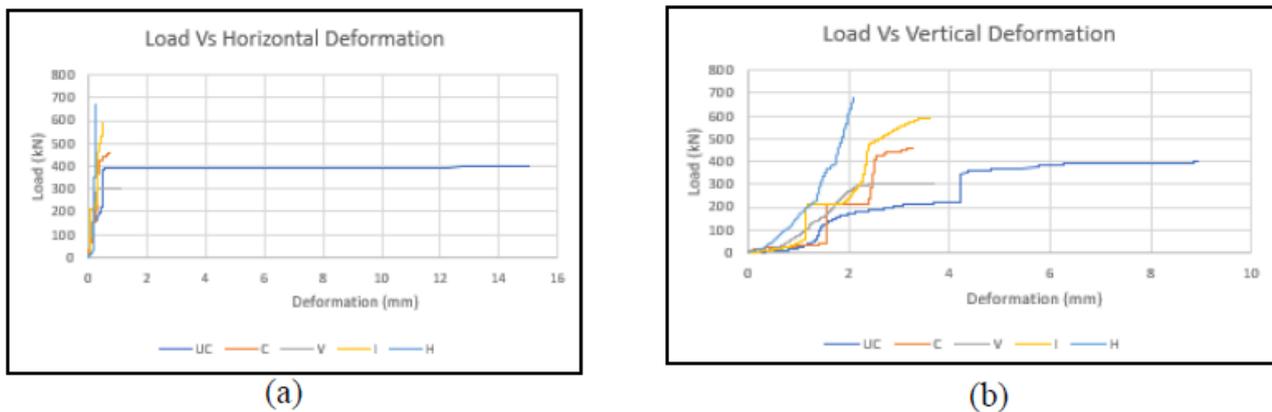


Fig. 4 Load and deformation behaviour of cylinder specimen (a) Horizontal; (b) Vertical

3.3 Stress-Strain Behavior

Fig. 5 investigates the impact of CFRP confinement on the stress-strain behavior of a cylindrical specimen. The response under different confinement scenarios using CFRP is represented by five curves. The unconfined case is represented by the dark blue curve, which demonstrates the lowest stress capacity. The material experiences a maximum stress of around 27.013 MPa when subjected to a relatively large strain of 0.05 in the horizontal direction and 0.03 in the vertical direction. The following flat area suggests a limited ability to withstand stress and a possible failure mode characterized by plastic deformation.

On the other hand, the red curve represents the response when the material is fully confined with CFRP. It exhibits a substantially increased ability to withstand stress compared to the unconfined scenario. The more pronounced initial incline indicates a more rigid reaction to axial pressure. Although the peak stress is not apparent in the displayed section of the graph, it is clear that the confined specimen has the ability to endure significantly greater stress before experiencing failure.

The grey curve depicts the reaction when subjected to vertically aligned CFRP confinement. When compared to the unconfined situation, it shows a significant enhancement in stress capacity, although it is probably not as high as the fully confined scenario. The strain at the point of maximum stress, especially in the horizontal direction (approximately 0.012), is also lower compared to the unconfined scenario. This suggests a more brittle reaction caused by the presence of vertical confinement.

The yellow curve represents the response when CFRP confinement is applied at an angle. Although there has been some improvement compared to the unconfined case, the stress capacity of the system seems to be lower than both the fully confined and vertically confined scenarios. The maximum stress is expected to occur between the situations where there is no confinement and when there is complete confinement. The strain at the point of maximum stress is lower in the horizontal direction (approximately 0.002) compared to the unconfined case, but higher in the vertical direction (approximately 0.012). This indicates that the response is influenced by the angle of confinement.

The light blue curve represents the response when CFRP confinement is applied horizontally. It demonstrates a discernible enhancement in stress tolerance compared to the unconfined situation, but it may be lower than the stress tolerance in fully confined and vertically confined scenarios. The strain at the point of maximum stress is expected to be lower in both the horizontal and vertical directions compared to the unconfined scenario.

Figure 5 conclusively illustrates that all CFRP confinement configurations substantially increase the stress capacity in comparison to the unconfined scenario. The most significant enhancement is achieved through full confinement, followed by vertical and inclined confinement, and finally, horizontal confinement. The strain response is influenced by the confinement configuration, where increased confinement typically results in reduced strains at peak stress. This suggests a stiffer and potentially more brittle response.

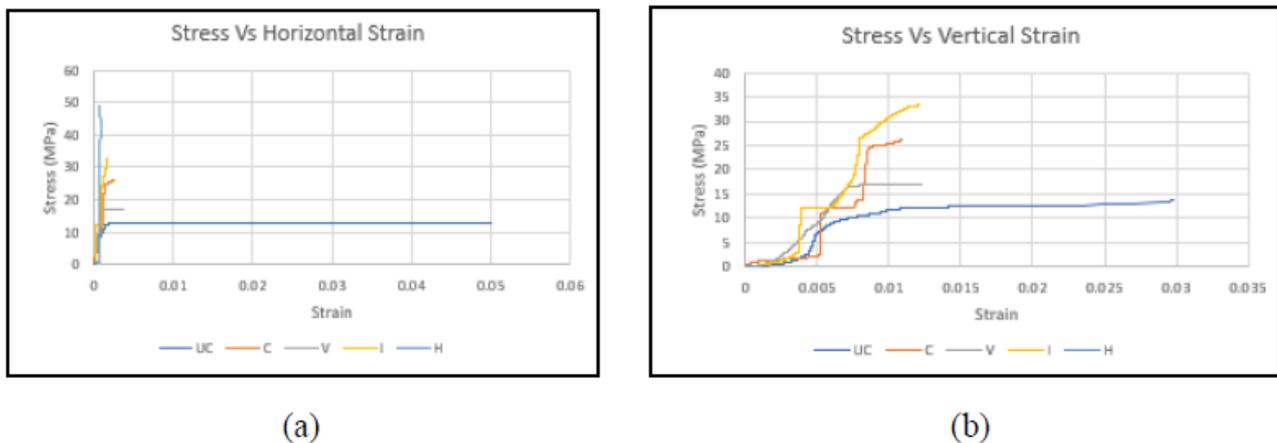


Fig. 5 Stress and Strain behaviour of cylinder specimen (a) Horizontal; (b) Vertical

4. Conclusion

In conclusion, this study comprehensively analyzed the behavior of HSC cylinders that were reinforced with various configurations of CFRP strips. The research seeks to elucidate the efficacy of different CFRP strip configurations in augmenting the robustness and longevity of HSC constructions, aligning with the primary objective of optimizing structural performance. Through the implementation of experimental tests and the analysis of theories, a multitude of significant conclusions were derived:

- The incorporation of CFRP strips led to a substantial improvement in the compressive strength of HSC cylinders in comparison to unconfined specimens. The rise in strength underscores the effectiveness of employing CFRP reinforcement for enhancing the durability of concrete structures, aligning with previous research that has emphasised the superior mechanical properties of CFRP materials

- The incorporation of horizontal CFRP strip patterns led to a significant enhancement in strength, exhibiting an estimated 68% improvement in comparison to specimens lacking confinement. This finding emphasises the remarkable efficiency of horizontally positioned CFRP reinforcement in optimising the strength of HSC constructions, which is consistent with the objective of the study to evaluate the effectiveness of different CFRP designs.
- The incorporation of horizontally arranged CFRP strips led to a delay in the occurrence of failure mechanisms that are similar to those observed when complete CFRP confinement is used. This observation highlights the ability of CFRP reinforcement to decrease premature failure and enhance the longevity of HSC constructions under compressive stress conditions.
- The stress and strain properties of cylinders reinforced with CFRP, whether inclined or horizontal, were greater than those of unconfined specimens. This indicates that the use of CFRP reinforcement results in improved mechanical properties and increased load-bearing capacity. This finding highlights the importance of tailoring CFRP configurations to optimise structural efficiency and minimise deformation under load.
- Furthermore, the load-bearing capacity of cylinders strengthened with CFRP was significantly higher than that of unconfined specimens, while also exhibiting decreased rates of deformation. This demonstrates that the utilisation of CFRP reinforcement not only enhances the structural strength, but also amplifies its load-carrying capacity and rigidity. Consequently, it enhances the overall structural strength and efficiency.
- Furthermore, the analysis of the crack pattern revealed diverse fracture modes that were influenced by the reinforcement of CFRP. Different configurations of CFRP exhibited variations in the mechanisms of crack propagation and failure modes. This emphasises the importance of employing selective CFRP reinforcement designs to optimise structural behaviour and performance.

These discoveries indicate that utilising CFRP reinforcement is a viable method to improve the durability and lifespan of HSC structures. By strategically arranging CFRP strips, engineers have the ability to enhance the structural performance, minimise premature failure, and enhance the overall resilience of concrete structures. Moreover, the information acquired from this study contributes to the advancement of understanding CFRP reinforcement techniques in the field of structural engineering, providing guidance for design practices grounded in evidence, and fostering innovation in the construction industry.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Fariz Aswan Ahmad Zakwan, Ruqayyah Ismail, Michelleine Michael **data collection:** Fariz Aswan Ahmad Zakwan, Ruqayyah Ismail **analysis and interpretation of results:** Fariz Aswan Ahmad Zakwan, Ruqayyah Ismail, Hazrina Ahmad, Michelleine Michael, **draft manuscript preparation:** Fariz Aswan Ahmad Zakwan, Ruqayyah Ismail, Hazrina Ahmad, Norlizan Wahid, Nor Hafida Hashim. All authors reviewed the results and approved the final version of the manuscript.

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