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Influence of Aspect Ratio and Corner Radius on the Structural Performance of Rectangular Columns with UHPFRC Jacketing

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Abstract. This study presents an investigation on the effect of concrete columns cross sectional properties on the performance of Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) jacket. This research explores the potential of UHPFRC as a novel and cost-effective material for rehabilitating damaged concrete structures, particularly focusing on its effectiveness in strengthening square and rectangular columns, where existing methods such as Steel Fibre Reinforced Polymer (FRP) have shown limitations. For that purpose, the cross sectional properties are namely aspect ratio, and corner to radius ratio. A total of 36 reinforced concrete column specimens were cast with varied size ratio. The jacketing cementitious UHPFRC material is 20 mm thick and made of UHPFRC. Two column specimens for each property were subjected to axial compression load. The performances of concrete column were measured in terms of maximum load carrying capacity, stiffness, ductility, and toughness. The results demonstrate that UHPFRC jacketing significantly enhances the load-carrying capacity of rectangular columns, with increases of 44%, 33%, and 31% for aspect ratios of 1.25, 1.50, and 1.75, respectively. The combined effect of UHPFRC jacketing and corner radius modifications led to an overall increase of up to 85%, 63%, and 53% in load-carrying capacity for the respective aspect ratios, highlighting the synergistic benefits of these interventions in improving structural performance.

1. Introduction

Buildings and bridges frequently require repairs and strengthening due to ongoing degradation and exposure to unexpected extreme loads, natural disasters, and changes in usage that demand increased load-bearing capacity. Structural failures in Malaysia have resulted in significant financial losses and fatalities, making the strengthening of existing structures a more cost-effective and environmentally friendly solution compared to demolition and reconstruction. Fiber Reinforced Polymer (FRP) composites have been effective in restoring the load-bearing capacity of circular columns, prompting the exploration of Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) for square and rectangular columns [1-2].

The column's cross-sectional properties, such as area, aspect ratio, and side-to-corner radius ratio, play a significant role in the effectiveness of jacketing materials. Studies have shown that UHPFRC can restore columns to their former load-carrying capacity under various conditions, performing better than FRP, which merely restores the columns' initial strength [3]. However, they only studied UHPFRC's general behaviour and jacketing methods.

The thickness of the UHPFRC jacket significantly impacts the mechanical performance of reinforced rectangular concrete columns, improving stiffness, toughness, and load-bearing capability but reducing ultimate displacement [4,5]. Comprehensive research is needed to explore the influence of cross-sectional shape and thickness on UHPFRC confinement effectiveness. Studies on Carbon Fiber Reinforced Polymer (CFRP) confinement highlight the importance of corner radius ratio on performance, as a larger corner radius can reduce stress concentrations, enhance confinement effectiveness, and improve the overall load-carrying capacity of the column [6-8]. However, there is limited research on UHPFRC in this context. This study aims to investigate the shape effect on square and rectangular columns using UHPFRC, optimizing mixture proportions, and examining the influence of cross-sectional sizes, aspect ratio, and corner radius ratio on confinement efficiency, with potential cost reductions by incorporating aggregates [9-11].

2. Experimental work

A total of 36 reinforced concrete column, contains of 6 different sizes of the details of the column specimens. The dimensions available are 100 x 125 mm, 100 x 150 mm, 100 x 175 mm, 100 x 125 R20 mm, 100 x 150 R20 mm, and 100 x 175 R20 mm, R represent radius. The samples were placed at the centre and a load was measured. Steel frames attached to the specimens' top and bottom helped measure displacement using two 50 mm LVDTs on each column face to calculate axial stresses. Strain was monitored with two KYOWA strain gauges, one horizontal and one vertical, at the column centre, connected to a UCAM-65C M 14 data logger. The setup is shown in Figure 1. To reduce measurement errors, 3 to 5 preloading cycles were conducted before actual loading. A total 18 specimens were reinforced utilising UHPFRC jacketing procedures, with each size ratio receiving this treatment. The 18 remaining columns that had not been strengthened were utilised as control reinforced concrete examples. The jacketing material is 20 mm thick and made of UHPFRC. The addition of a steel fibre content of 2.0% to the UHPFRC.

All column specimens have a fixed height of 300 mm. The column specimens tested in the study had a size ratio of 1:3. Therefore, all the columns examined in this study are of a little length, and it is considered that the impact of slenderness is insignificant. In this study, tie reinforcement stirrups are not used for any of the columns. This decision is made in order to examine the behaviour of the UHPFRC material in isolation, allowing for a more precise understanding of its properties without the interference of supplementary reinforcement.

2.1. Specimen preparation and test set up

This study UHPFRC mixing design is presented in Table 1. The mix proportions, including ratios of cement, water, high-range water reducers (HRWR), silica fume, fine sand, glass powder, fibres, quartz sand, and marble powder, significantly impact UHPFRC properties. The inclusion of macro and micro fibres enhances tensile strength, ductility, and impact resistance, with the mixing procedure affecting fibre distribution and orientation. High-shear or planetary mixers improve concrete homogeneity and workability, while steam curing improves early-age strength and bonding performance.

Table 1. Mixture proportion of UHPFRC

Cement OPC (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Hyper Plasticizer (kg/m^3)	Fiber steel (kg/m^3)
800	160	433	800	45	2%

The optimal UHPFRC mixing procedure involves sequentially mixing dry materials, adding water and superplasticizer gradually, and finally incorporating steel fibres at a reduced speed. To insure high compressive strength of concrete, the Mixer speed was set to the max speed for 3 minutes. To reach the desired workability range of 400–800 mm, a superplasticizer is required. UHPFRC cubes tested for compressive strength according to BS EN 12390 Part 3 with a loading rate of 2 kN/s. The tensile splitting test, performed according to ASTM C496. The mix ratio ensures a minimum compressive strength of 100 MPa and a workability range of 400–800 mm as per ASTM C1611. Samples were centred, and a load cell between steel and loading plates measured axial load. Steel frames attached to the specimens' top, and bottom helped to set the LVDTs on each column face to calculate displacement as seen in Figure 1. Strain was monitored with two KYOWA strain gauges, one horizontal and one vertical, at the column centre, connected to a UCAM-65C M 14 data logger. To reduce measurement errors, 3 to 5 preloading cycles were conducted before actual loading.

Figure 1. Experiment setup for loading test for columns

3. Results and discussion

Compression tests on 100 mm cubes after 28 days showed UHPFRC had an average compressive strength of 108 MPa, compared to 34 MPa for conventional concrete. For tensile strength, UHPFRC had an average splitting tensile strength of 9.2 MPa, nearly double that of regular concrete. UHPFRC also had a mean flexural strength of 9.6 MPa, almost twice that of regular concrete's 5.1 MPa.

3.1. Impact of column aspect ratio on load capacity with and without UHPFRC jacket

This study examined three aspect ratios: 1.25, 1.50, and 1.75. The aspect ratio is the ratio between the length of the longer side and the length of the shorter side of a rectangular column seen in Figure 2. The aspect ratio of a rectangular concrete column has a direct correlation with its load-carrying capacity. Figure 3 demonstrates that rectangular columns with aspect ratios of 1.25, 1.50, and 1.75 have load-carrying capacities of 350 kN, 401 kN, and 447 kN, respectively. This indicates that the load-carrying capability of rectangular columns grows as the aspect ratio increases. However, in this situation, the rise in load-carrying capacity can be attributed to the increase in cross-sectional area, as the aspect ratio likewise leads to an increase in the cross-sectional area.

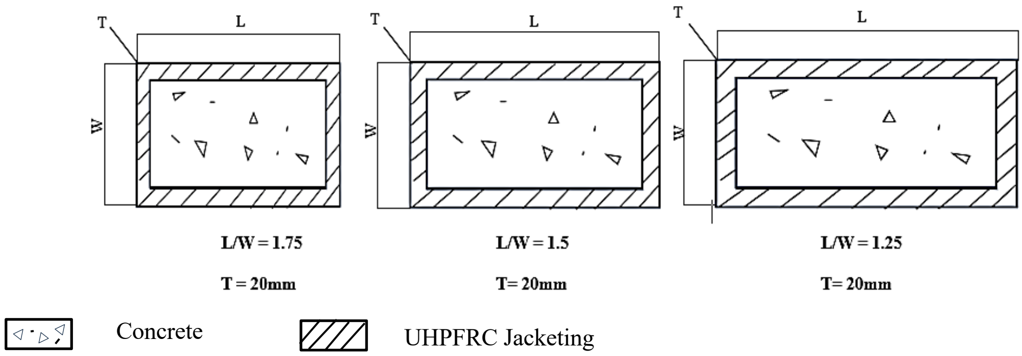

Figure 2. Rectangular column after strengthening

After rectangular concrete column specimens were confined with 20 mm thick UHPFRC jacket, the averaged load capacity increases to 506 kN, 534 kN and 584 kN which represents 44%, 33% and 31% of increment for specimen with aspect ratio of 1.25, 1.50 and 1.75, respectively. The increment is across all the aspect ratio, however, the rate of increment reduces with the increment of aspect ratio from 1.25 to 1.75. Stress concentrations inherent to larger shapes limited full utilization of the jacket because of the stress concentrations leading to less uniform confinement. The near-square sections maximize confinement efficiency through uniform confinement pressure [12]. As a result, the jacket was able to restrict lateral deformation more effectively. Although these increments were substantial, they did not surpass the enhancements.

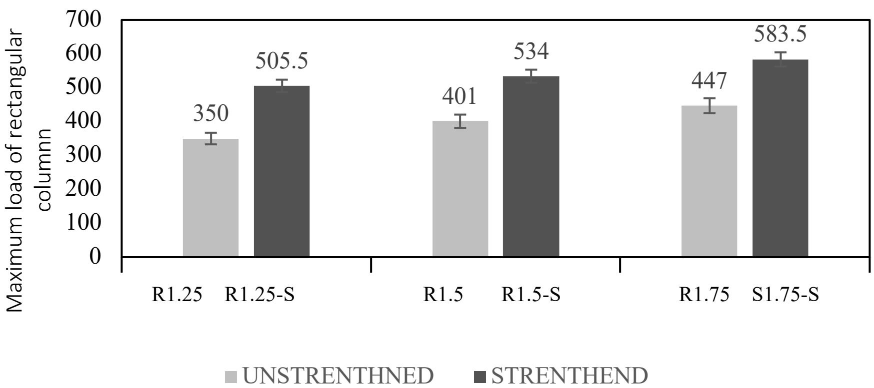

Figure 3. Maximum load carrying capacity of rectangular column and UHPFRC jacketed rectangular column

3.2. Effect of column corner radius on the UHPFRC ultimate strength

In this study, rectangular columns with depths of 125 mm, 150 mm, and 175 mm are fitted with a 20 mm corner radius, resulting in varying side-to-corner radius ratios of 6.25, 7.50, and 8.75, respectively as seen in Figure 4. The comparison between unconfined specimens with and without corner radii reveals a notable trend: as the ratio increases (indicating sharper corners), there is a consistent increase in the maximum load-bearing capacity.

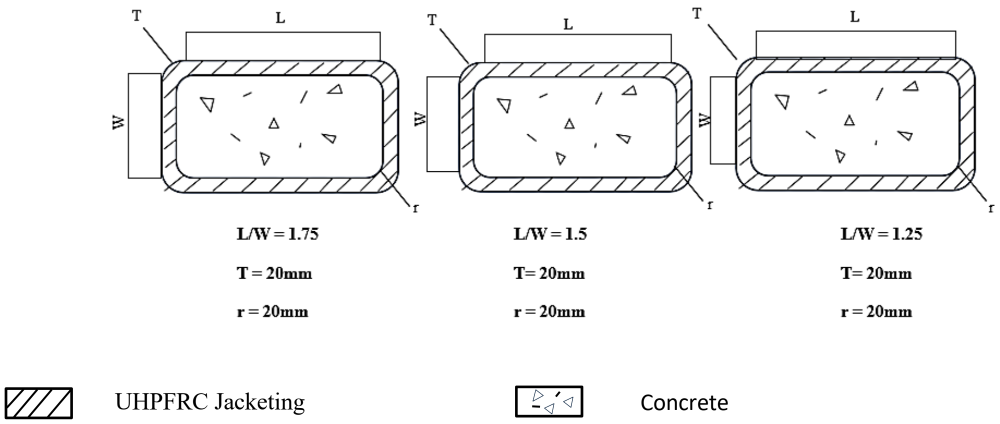

Figure 4. Corner radius rectangular after strengthening

For instance, as shown in Figure 3 and Figure 5, in the case of 125 mm specimens, the average maximum compressive load of unconfined specimens without corner radius (R1.25) and with corner radius (RC6.25) were 350 kN and 427 kN, respectively, marking an approximate 22% increment. Similarly, for 150 mm depth specimens, the load capacity increased from 401 kN for the R1.50 specimens to 468 kN for RC7.50 (17% increment). In the case of 175 mm depth specimens, the load capacity rose from 447 kN for the R1.75 specimens to 509 kN for RC8.75 specimens (14% increment). Thus, it shows that after introduction of corner radius, the increment percentage of load carrying capacity decrease with the increase of side-to-corner radius ratio.

Upon applying the UHPFRC jacket, rectangular specimens with corner radius (RC6.25-S) displayed a remarkable 28% increase compared to those without corner radius (R1.25-S). Subsequently, the maximum load carrying capacity of 150 mm and 175 mm depth rectangular specimens with corner radius increased by 22% and 18% compared to their non-corner radius counterparts.

Furthermore, when comparing rectangular columns without corner radius to UHPFRC confined rectangular columns with corner radius, the synergistic effect of both interventions becomes evident. For 125 mm depth rectangular specimens, the load carrying capacity of RC6.25-S specimens was 85% higher than that of R1.25 specimens. Similarly, for 150 mm depth specimens RC7.50-S specimens exhibited a 63% higher load carrying capacity than R1.50 specimens. And for 175 mm depth specimens, RC8.75-S specimens showed a 53% higher load carrying capacity than R1.75 specimens. These results underscore the significant benefits of integrating corner radius and UHPFRC jacketing in enhancing the load-bearing capacity of rectangular columns across varying depths.

The concurrent application of a corner radius and UHPFRC jacketing resulted in the highest strength values across all configurations. This enhancement in strength can be attributed to the combined effects of reducing stress concentrations and improving confinement efficiency. The introduction of a corner radius helps to reduce stress concentrations at the edges of rectangular columns, allowing for more uniform stress distribution and higher load-bearing capacity. Meanwhile, the UHPFRC jacket provides additional confinement, enhancing the overall strength and ductility of the columns. When combined, these interventions work synergistically, resulting in superior performance compared to their individual application.

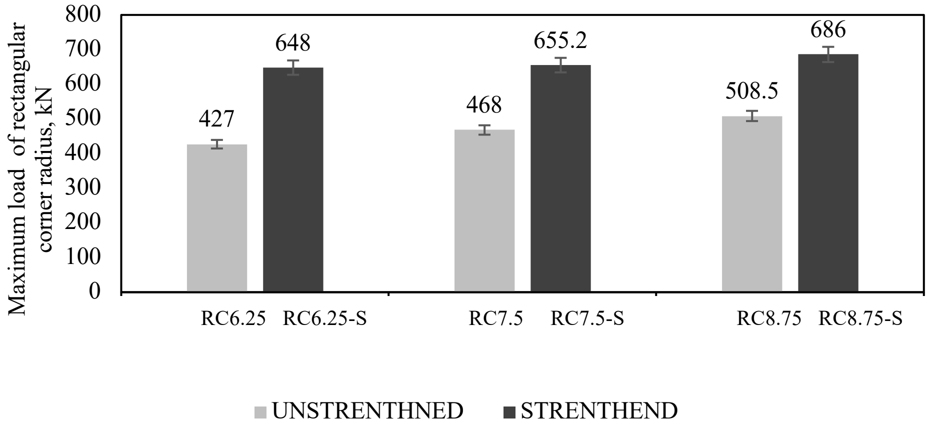

Figure 5. Maximum load carrying capacity of rectangular column with corner radius

3.3. Axial stress-axial strain behaviour of UHPFRC-jacketed rectangular columns with varying corner radius

To evaluate the effectiveness of UHPFRC jackets on the structural performance of rectangular columns, axial and lateral strains were meticulously measured using strain gauges, and axial stresses were derived by dividing the applied axial loads by the column's cross-sectional area. The results demonstrated that UHPFRC-jacketed rectangular columns (R1.25, R1.5, R1.75) exhibited lower axial strains compared to their unstrengthened counterparts, due to the higher elastic modulus of the UHPFRC jacket, which provides additional stiffness and confinement. Smaller aspect ratio columns exhibited higher strains due to the more uniform distribution of load stresses, with an initial high increment in load and lower strain at the start of the test, followed by a notable surge in strain as the load reached a stable state. The application of a UHPFRC jacket significantly reduced lateral strain, as the jacket provided additional confinement that restricted the outward bulging of the column when a load was applied. This confinement effect increased the load-bearing capacity of the column and decreased the sideways strain compared to the axial strain.

The influence of the corner radius on the compressive strain of rectangular columns was also observed. A comparison between unconfined columns with no corner radius (R1.25) and those with a corner radius (RC6.25) revealed a substantial increase in compressive strength prior to jacketing. This augmentation in strength was accompanied by an elevation in strain at higher stress levels. Rectangular columns with larger corner radii exhibited higher compressive strength and ductility under the same load compared to columns with no corner radii. The larger corner radius allowed for a more even distribution of stress across the column's cross-section, reducing stress concentration at the corners and resulting in enhanced strength and ductility of the column [13]. In summary, UHPFRC jackets were effective in improving the structural performance of rectangular columns by increasing compressive strength and ductility, reducing lateral strains, and providing additional confinement. The combined use of UHPFRC jacketing and corner radius modifications led to superior performance in terms of load-bearing capacity and stress distribution, underscoring the importance of these techniques in structural strengthening applications.

4. Conclusion

This study examined the impact of column shape on the effectiveness of UHPFRC as a strengthening material for rectangular columns, focusing on quantifying mechanical stress-strain properties. Parameters analysed included aspect ratio, and side to corner radius ratio. A total of 36 column specimens, both with and without confinement, were tested. The primary mechanical parameters analysed were the load-carrying capacity and stress-strain response. Key findings are summarized as follows.

i. Rectangular columns with larger corner radii tend to have higher compressive strength and ductility under the same load compared to a column with smaller corner radii. This suggests that minor modifications to the column's geometry, such as the introduction of a corner radius, can have a substantial impact on its stress and strain behaviour under load.
ii. The concurrent application of a corner radius and UHPFRC jacketing to rectangular columns results in the highest strength values across all configurations, suggesting a synergistic effect. This indicates that the combined use of these techniques can lead to superior performance compared to their individual application, and the benefits are more pronounced in columns with certain shapes.
iii. The application UHPFRC jacketing further alters this relationship, enhancing the load-bearing capacity of all column size and shape but also affecting the ductility, particularly in rectangular columns such as those with rounded corners. Specifically, the application of a corner radius to rectangular columns effectively increases their compressive strength but results in less ductile specimens.

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