Towards Effective Design of Ultra High Performance Fiber Reinforced Concrete.

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Towards effective design of Ultra High-Performance Fiber Reinforced Concrete

Spyridon A. Paschalis [1], Andreas Lampropoulos[2]

[1]University of West London, St Mary's Road, Ealing, London W5 5RF, UK

[2] University of Brighton, UK

Abstract

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) has found application in demanding structural scenarios requiring exceptional performance, durability, and ductility. The utilization of this material for structural strengthening is increasingly gaining popularity. It allows for the construction of slender, yet ductile elements without significant alterations to the element's dimensions. One of the primary drawbacks of this material is the lack of extensive design codes. Additionally, its high cost is another notable limitation.

The present study focuses on the application of UHPFRC for strengthening purposes and aims to investigate its optimal characteristics. In this study, the results from testing large-scale beams strengthened with UHPFRC layers have been used to develop a numerical model capable of predicting the performance of strengthened reinforced concrete beams. This model explores critical material parameters, including layer depth, fiber content, the interface condition, and the use of steel bars in the layers. The results suggest that incorporating additional reinforcing bars into the UHPFRC layers yields superior performance when compared to increasing the depth of the elements or using higher fiber dosages. The interface conditions affect the performance of strengthened elements significantly.

Keywords: Ultra High-Performance Fiber Reinforced Concrete, Strengthening, Effective design

1.0 Introduction

The structural integrity of structures is highly important worldwide, as it directly affects people's safety and lives. Many structures constructed in the past have reached the end of their service life or have been affected by accidental actions and do have the required safety level. A traditional approach to upgrading infrastructure safety involves demolishing existing buildings and constructing new ones that adhere to updated regulations and utilize superior materials. However, as we shift towards sustainable development, this may not be the most efficient approach when considering both sustainability and cost.

Currently, there are many strengthening techniques. Some of the primary drawbacks of existing strengthening techniques include low performance, challenges in application, lengthy application times, high costs, and disruption to occupants during the process. Additionally, the consumption of materials and their environmental impact are significant disadvantages that hinder the widespread adoption of these techniques. Research should prioritize the development of new, effective, and reliable methods. Ultra High-Performance Fiber Reinforced Concrete (UHPFRC) exhibits superior properties compared to traditional materials and has found applications in structural projects demanding high mechanical strength, ductility, and durability. A particularly promising application involves the strengthening of existing structures using UHPFRC. One challenge faced in applying this material for reinforcement is the absence of established design standards.

The current investigation focuses on the application of UHPFRC to strengthen Reinforced Concrete (RC) beams and the investigation of crucial parameters affecting the material's performance for strengthening purposes. The study will specifically explore critical material parameters affecting the design of strengthening techniques.

The superior properties of UHPFRC are primarily attributed to its enhanced microstructure and tensile characteristics, which are significantly influenced by the type of fibers and fiber content. Varied amounts of fibers lead to distinct tensile laws [1-4].

Compressive strength values exceeding 200 MPa and tensile strength values up to 15 MPa have been documented for UHPFRC [5]. The orientation and distribution of fibers emerge as crucial parameters impacting the performance of UHPFRC. Additionally, when designing structural elements with substantial depths, it is imperative to consider the size effect [6-10].

UHPFRC has been applied for strengthening purposes. Tanarslan [11] applied UHPFRC for strengthening of RC beams. The material was utilized in the form of prefabricated laminates with various configurations, connected to existing members through epoxy. In all cases, a notable enhancement in the performance of the reinforced members was observed, showing an increase in the range of 32-208%. However, a drawback noted in the examined technique was the difficulty in applying the prefabricated laminates.

Al-Osta et al. [12] explored the performance of RC beams strengthened with UHPFRCC layers, employing various methods, including the sand patch method and the use of prefabricated strips. In all instances, superior performance was observed; however, the sandblast method demonstrated superior performance when compared to prefabricated strips.

Paschalis et al. [13] conducted an investigation into the performance of UHPFRC as a strengthening material, employing various configurations. These included the strengthening of RC beams using UHPFRC layers, both with and without steel bars, and an examination of the interface connection between UHPFRC and RC. The findings revealed that the addition of UHPFRC layers increased the stiffness of the strengthened members, while the incorporation of steel bars led to a significant increase in the load-carrying capacity of the strengthened members.
This study highlighted that the interface connection between UHPFRC and RC exhibited superior performance compared to concrete-to-concrete interfaces. However, a separate study [14] indicated that the addition of steel connectors at the interface between UHPFRC and concrete could result in a connection approaching the monolithic, with superior performance observed compared to samples without steel connectors at the interface. The optimal performance was noted for the strengthening of RC beams using UHPFRC jackets.

Murthy et al. [15] utilized UHPFRC for the repair of damaged RC beams, and a superior performance was observed for the repaired beams, with a failure mode similar to control beams without any layer. UHPFRC has also been employed in the strengthening of RC slabs. In a study by Yin et al. [16], UHPFRC was applied for the strengthening of RC slabs, leading to a reduction in diagonal cracks and demonstrating superior performance in the post-elastic region.

Based on existing studies, the application of UHPFRC for strengthening purposes emerges as a promising technique, showcasing superior performance compared to traditional methods like using RC. However, for the effective design of such strengthening techniques, crucial parameters must be carefully considered. These include layer depth, the amount of reinforcement, interface conditions, and the incorporation of steel bars in the UHPFRC.

Optimal performance should be balanced with other factors such as ease of application and cost. In the ongoing investigation, both experimental and numerical analyses have been conducted to investigate the effects of these parameters on the performance of beams strengthened using UHPFRC.

2.0 Examined Beams

In the present study, the results from testing large-scale beams strengthened with UHPFRC layers have been used to develop a numerical model capable of predicting the performance of strengthened reinforced concrete beams.

Two samples of various types of beams were investigated: RC beams without any layer (control beams), RC beams strengthened with UHPFRC layers, RC beams strengthened with UHPFRC layers and dowels at the interface, and RC beams strengthened with UHPFRC layers and steel bars.

The dimensions of the examined beams are presented in Figure 1.

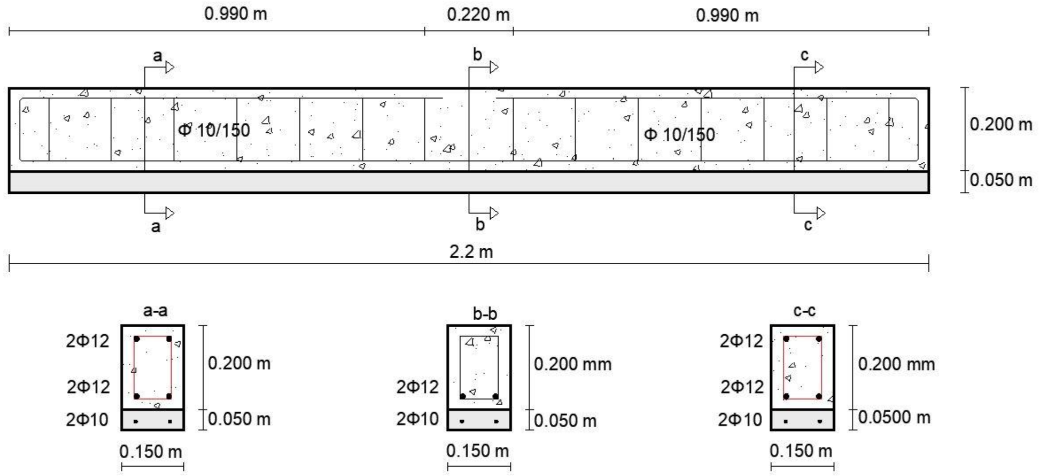

Figure 1 Strengthened Beams with UHPFRC

Compressive tests on cubes and direct tensile tests on dog bone specimens were conducted to obtain the properties of concrete and UHPFRC. From the material testing, the average compressive strength of concrete was determined to be 30.9 MPa with a standard deviation of 2.4 MPa, the average compressive strength of UHPFRC was 136.9 MPa with a standard deviation of 5.7 MPa, and the direct tensile strength of UHPFRC was 11.5 MPa with a standard deviation of 1.9 MPa.

For the numerical modelling of concrete, a nonlinear behaviour was assumed in both tension and compression, and a bilinear behaviour was adopted for the steel bars. To model the interface between UHPFRC and concrete, cohesion was set at 1.8 MPa and friction at 0.98, based on experimental results from a previous study [13]. Additionally, a bond-slip law following the CEB-FIB [17] guidelines was employed. The results obtained from direct tensile testing of UHPFRC were utilized for modelling UHPFRC in tension, considering a strain-hardening behaviour.

The geometrical model, the mesh generation, and the stresses during analysis are presented in Figure 2. A mesh size of 0.05 m was used in this study.

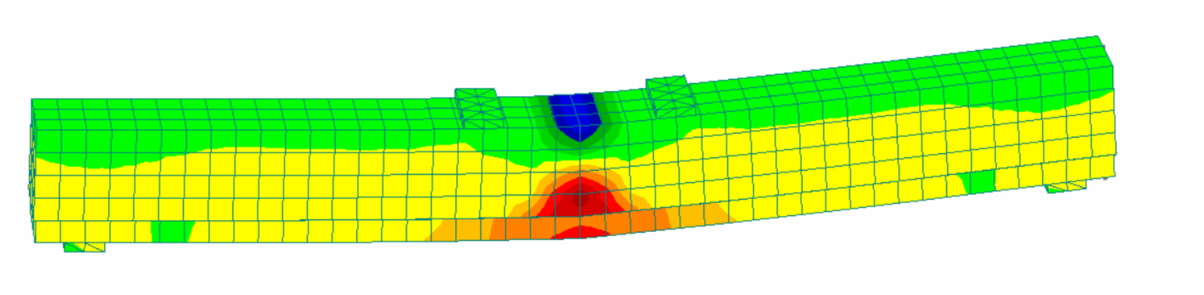

Figure 2 Modelling of a strengthened beam in Atena software

3.0 Validation of the numerical model

The experimental results from testing the large-scale beams were compared with the numerical results, and the findings are presented in Figure 3. From this figure, a good agreement between the numerical and experimental results can be identified.

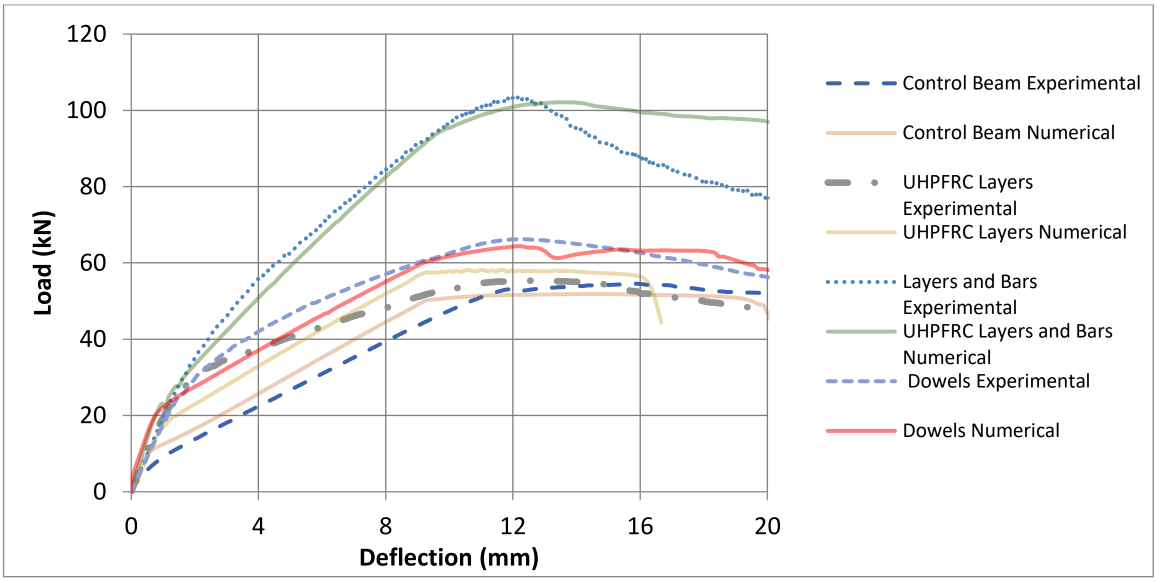

Figure 3 Experimental vs numerical results

4.0 Results

4.1 Effect of Layer Depth

In the design of strengthening techniques, a critical decision involves selecting the appropriate layer depth. Considerations such as the performance of the strengthened elements, cost, dimensions of existing members, and fiber orientation should be considered. In the present section, different parameters are investigated numerically.

Layer depths less than 30 mm may pose issues with fiber distribution and are not expected to significantly contribute to the load-carrying capacity of the strengthened elements. Conversely, higher depths may exhibit a size effect. In the current investigation, different layer depths were examined numerically: 30 mm and 70 mm. These values are out of the range of the 50 mm that was investigated experimentally, in order to identify the effect of the layer depth.

Another crucial parameter is the interface conditions. In the current numerical investigation, two cases were examined: a non-monolithic connection at the interface with a cohesion value of 1.8 MPa and a friction value of 0.98, and perfect bonding. The results for the various layer depths and different conditions are presented in Figures 4a and 4b.

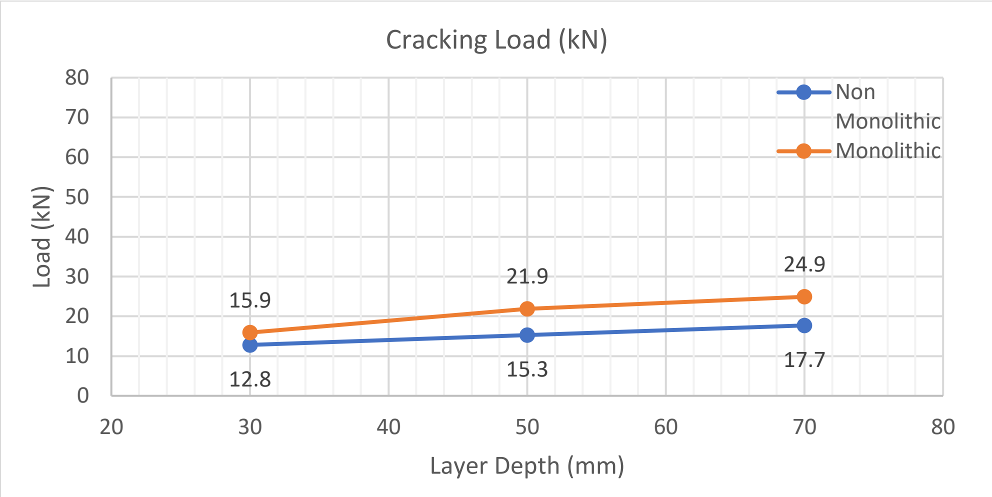

Figure 4a Cracking Load for the different layer depth

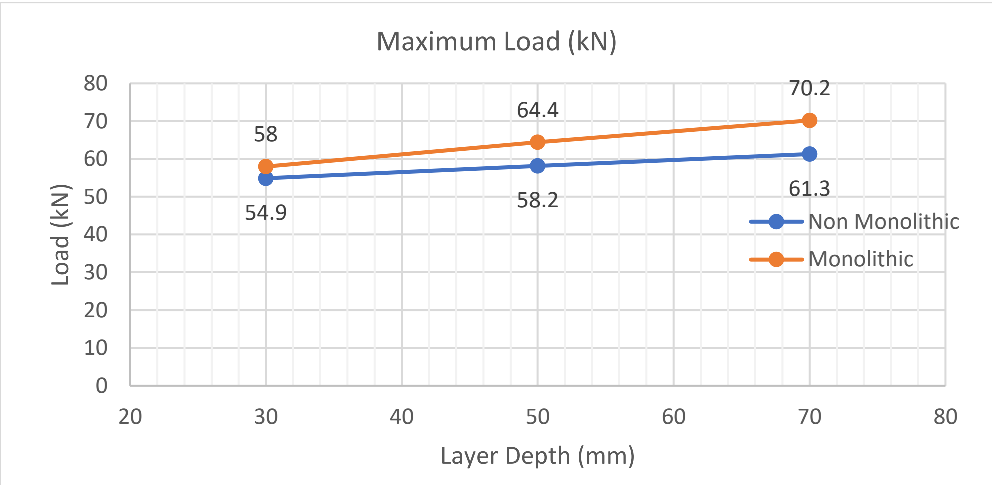

Figure 4b Maximum Load for the different layer depth

The results clearly indicate that both layer depth and interface conditions have a significant impact on the performance of the strengthened beams. In the case of a non-monolithic connection at the interface, cracking commenced at 12.8 kN for the 30 mm layer, 15.3 kN for the 50 mm layer, and 17.7 kN for the 70 mm layer. In contrast, for a monolithic connection, the corresponding values were 15.9 kN, 21.9 kN, and 24.9 kN, respectively.

In the case of a non-monolithic connection, the maximum load for the 30 mm layer was 54.9 kN, and for the 50 mm and 70 mm layers, it increased to 58.2 kN and 61.3 kN, respectively. For monolithic connection, the corresponding values were 58.1 kN, 64.4 kN, and 70.2 kN. Based on these results, for non-monolithic connection, the load-carrying capacity increased by 11.7% as the layer depth increased from 30 mm to 70 mm. In contrast, for monolithic connection, the increase was almost double, reaching 21%.

4.2 Effect of tensile strength of UHPFRC

A crucial aspect in the design of strengthening techniques using UHPFRC is the fiber content. Different fiber contents primarily impact the tensile characteristics of the material, with cost also being a significant consideration. Striking a balance between cost and performance is a challenging issue. The tensile strength of the UHPFRC in the present investigation was 11.5 MPa, whereas even higher values have been reported in the literature. In this study, three different values were examined: 11.5 MPa, 12.5 MPa, and 13.5 MPa. The results are presented in Figure 5.

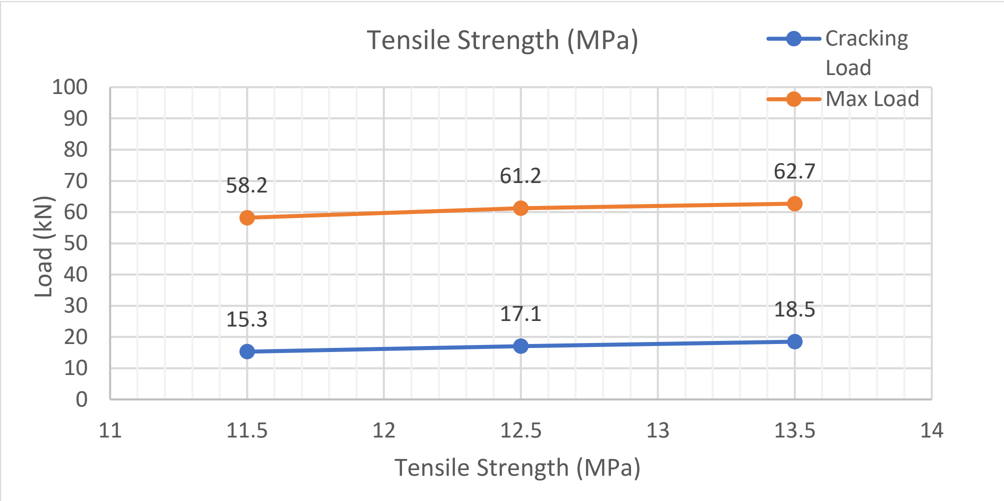

Figure 5 Maximum Load of strengthened beams for different tensile strengths

As depicted in Figure 5, the tensile strength significantly influences both the cracking load and the load-carrying capacity. With an increase in tensile strength from 11.5 MPa to 13.5 MPa, the cracking load saw a 20% increase, and the maximum load increased by 7.7%.

4.3 Effect of amount of reinforcement in the UHPFRC layer

An option to enhance the load-carrying capacity of strengthened RC beams involves incorporating steel bars in the UHPFRC layers. In the beam used for the experimental investigation, which served as validation for the numerical model, two steel bars with a diameter of 10 mm were employed. In the current investigation, steel bars with diameters 12 m and 14 mm were used to investigate the effect of various amounts of reinforcement. The results are presented in Figure 6.

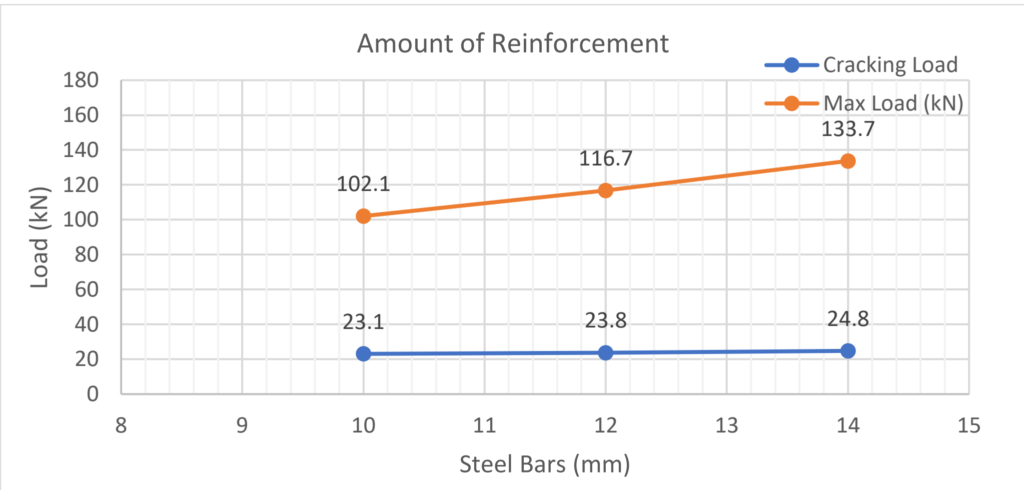

Figure 6 Maximum Load of strengthened beams for bars with different diameters

As evident from Figure 6, the addition of steel bars leads to a substantial increase in load-carrying capacity. The maximum load-carrying capacity of beams strengthened with a 50 mm UHPFRC layer without bars increased from 51.9 kN to 58.2 kN. The introduction of 2 bars with a diameter of 10 mm elevated the load-carrying capacity to 102.1 kN, almost doubling it. Substituting the 10 mm bars with 12 mm bars resulted in a further 14% increase. When the 10 mm bars were replaced with 14 mm steel bars, a noticeable additional increase of 31% was observed. These results highlight that the incorporation of steel bars can significantly enhance the load-carrying capacity of beams.

5.0 Conclusions

For the design of strengthening techniques using UHPFRC, critical decisions must be made regarding layer depths, fiber content, interface conditions, and the incorporation of steel bars in the layers.

Based on the results of the present study, the following key findings were observed:

1. Increasing the layer depth from 30 mm to 70 mm resulted in an 11.7% increase in load-carrying capacity. With a monolithic connection (achieved with dowels), this increase was nearly doubled at 21%.
2. The tensile strength of UHPFRC also impacts the performance, although to a lesser extent. When the tensile strength increased from 11.5 MPa to 13.5 MPa, the cracking load increased by 20% increase, and the maximum load increased by 7.7%.
3. Optimal performance was achieved with the incorporation of steel bars in the UHPFRC layers. The addition of 10 mm bars resulted in a 43% increase, and further replacing the 10 mm bars with 14 mm bars led to an additional 31% increase in load-carrying capacity.

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