CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Strengthening of RC Beams using Ultra High Performance Concrete (UHPC) with CRFP Laminate

by

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I want to dedicate this achievement my parents, teachers and friends who always encourage and support me in every crucial time

CERTIFICATE OF APPROVAL

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In the name of Allah, *The Most Gracious and Merciful* and The Sustainer of the worlds. I humbly bestow my head in front of the Allah Almighty and say *Shukar Alhmado Lillah* who enabled me with His greatest blessing i.e. knowledge and wisdom to accomplish my thesis successfully.

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Abstract

Reinforced concrete infrastructure degrades over time under environmental action or natural disasters. In other cases, extra loads are required to withstand when service requirement of a structure changes. In both cases the strengthening and rehabilitation of RC structures is required. Carbon fiber reinforced polymer (CFRP) laminates are commonly used materials for this purpose. However, these laminates are expensive and are not readily available, also since they are epoxy based materials, their bonding with concrete under moisture is compromised. That is why recently cement based strengthening materials are also being explored. In this study the ultra-high-performance concrete (UHPC) along with CFRP-epoxy laminates, as hybrid strengthening system has been explored. Eight reinforced concrete beams were pre-loaded to 100% and 75% of ultimate load carrying capacity. After pre-loading, the cover of concrete from the soffit (bottom) was removed and 30 mm thick UHPC layer was applied at the soffit of the beams to cover the steel reinforcement. After curing UHPC layer, either a 1000 x 100 mm strip was applied at soffit, or a three side U-wrap at three different locations were applied. It was observed that the UHPC layer and CFRP strip in flexure increased the load carrying capacity of 100% damaged beams with an increment of 5% compared to sound beams. Whereas, when 75% pre-loaded beams were strengthened with UHPC-layer and CFRP strip at bottom, the increment in load carrying capacity was 53%. In the case of U-wrap after applying UHPC layer, the 100% pre-loaded beam, showed a regain in strength up to 19% whereas, 75% pre-loaded beams showed an increment of 62%. The results of this study show that strengthening of damaged or strength deficient concrete structure could be efficiently carried out by UHPC and CFRP hybrid system.

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Abbreviations and Symbols

ACI	American Concrete Institute
AFRP	Aramid Fiber Reinforced Polymers
ASTM	American Society for Testing and Materials
BFRP	Basalt Fiber Reinforced Polymers
CFRP	Carbon Fiber Reinforced Polymers
ECC	Engineered Cementitious Composites
FRP	Fiber Reinforced Polymers
GFRP	Glass Fiber Reinforced Polymers
HRWR	High-Range Water Reducer
JSA	Japanese Standard Association
NSC	Normal Strength Concrete
RC	Reinforced Concrete
UHPC	Ultra High Performance Concrete
UHPFRC	Ultra-High-Performance Fibre-Reinforced Concrete

Chapter 1

Introduction

1.1 Background

The construction industry overwhelmingly relies on RC structures due to its versatility, economy, and adaptability. An estimated 25 billion tons of concrete are produced worldwide every year (i.e., 3.8 tons of concrete made per person) [1]. As the service time of the structure increases, the performance of reinforced concrete gets affected by many factors, such as adverse environment, aging, change in loading condition, lack of maintenance or change in its use etc. These factors not only affect the mechanical performance of RC structure, but also threaten the personal safety of the users [2]. Besides above factors certain RC structures do not meet the new seismic code regulation and are being strengthened as is being done in Taiwan [3]. In such cases, two choices are possible: reconstruction or strengthening the subject RC structure or element. The reconstruction of the structure might include negative aspects like excessive costs of the materials and labors, inconvenience and time factor. Therefore, strengthening or retrofitting of existing RC structures is done to meet the performance requirements for intended use.

The term retrofitting or strengthening entails making the structural members capable of supporting loads and improving their performance so that little maintenance is required over the course of their service life. Strengthening and retrofitting techniques can be classified into passive and active where numerous different materials have been researched and put into practice [4]. In the past RC Jacketing and metal plates have been preferred for strengthening of the RC members as outside bonded techniques. According to the experimental tests, it has been found that the flexural resistance of the concrete beam can be enhanced through the utilization of this strategy. However, due to intrinsic difficulties of this technique including increased cross sectional area and weight of the member, research for alternate retrofit materials was necessitated across the globe. In recent years, retrofitting/strengthening of RC structures has witnessed significant advancements in material technologies, aiming to enhance their seismic resilience, durability and overall performance. These advanced materials include Ultra High Performance Concrete (UHPC), fiber reinforced polymers (FRP) and Engineered Cementitious Composites (ECC). These latest retrofit materials have shown profound economic, environmental, and compatibility effects. Also, for sustainability, it is crucial to enhance the relationship between repairs, strength, structures age and durability properties of concrete [5].

RC beams are crucial structural elements. Therefore, it is essential to strengthen the damaged or strength deficient beam to improve its load carrying capacity and in-service performance by using advanced techniques and materials. The researchers in recent past have been developing different techniques to enhance the performance of RC beam using advanced materials. Emar et al. [6] observed an increase in flexure strength up to 125% in beams reinforced with externally bonded (EB) FRP. Alhoubi et al. [7] compared the flexural performance of UHPC beams reinforced with basalt FRP (BFRP), steel, and glass FRP (GFRP). The results showed that UHPC enhanced the flexural performance of BFRP-reinforced beams in terms of moment capacity, deflection response, and cracking patterns. Similarly, S.Ahmad et al. [8] noticed that flexural performance of reinforced RC beams was significantly increased after strengthening with three UHPFRC jacketing configuration. Al-Huri et al. [9] carried out statistical analysis (ANOVA) and found out that configuration and thickness of UHPC layers had significant impact on flexure performance of corrosion damaged RC beams. By applying UHPC layers on three sides in U shape, it increased ultimate flexural strength by 6-63% and stiffness by 28-112% compared to un-corroded control beams. As evident from above mentioned studies, UHPC and FRP laminates can significantly improve load carrying capacity of reinforced concrete (RC) beams. Also, combination of UHPC and FRP has shown excellent performance and have shown excellent results by reducing the shortcoming of an individual repair material. Therefore, it is possible that UHPC layer when used in combination with different configurations of CFRP can further enhance the mechanical properties of RC beam.

1.2 Research Motivation and Problem Statement

The construction industry heavily relies on reinforced concrete (RC) structures due to its versatility, economy, and adaptability. However, factors like adverse environments, aging, and changing loading conditions can affect its performance and safety. Researcher over the years have studied new materials and different repair / strengthening techniques including aspects of durability and sustainability. Mainly, these techniques include use of UHPC and ECC layers in combination with FRP laminates.

Buildings do experience damages and strength reduction due to various factors during their operation period. In order to keep these buildings functional and operational for their intended use during the design life, there is need of adopting strategies like retrofitting. So far, majority of buildings in Pakistan are retrofitted by using conventional methods. So, there is need to focus the latest appropriate materials and techniques to achieve better results. Therefore, this study focuses on such initiatives.

Therefore, keeping in mind the retrofitting techniques implemented in Pakistan construction sector in relation to sustainability and lack of use of new materials, research is required to determine effectiveness and reliability of new materials specially UHPC with FRP laminate in Pakistan.

1.2.1 Research Questions

- How much structural performance of RC beam can be increased using UHPC with CFRP laminate?
- Can strengthened strength-deficient RC element achieve same flexural bearing capacity as of original RC beam section?
- Does UHPC with CFRP strengthened element fails in premature de-bonding or concrete rupture?
- Which UHPC and CRFP combination (Soffit or U-shaped) gives better flexure performance after strengthening of beams?

1.3 Overall Objective of the Research Program and Specific Aim of this MS Thesis

The overall objective of this research is to study the method / technique to strengthen damaged or strength deficient RC beams using UHPC and CFRP laminate. This will not only introduce use of new techniques but will also help preparation of UHPC in Pakistan using local material enabling sustainable development in Pakistan construction sector.

In order to achieve this objective, the structural performance of concrete beams and its strength regains activity will be investigated by using combination of UHPC with CFRP laminate. Results will be compared to decide up to what extent which combination can be applied in civil engineering applications.

1.4 Scope of Work and Study Limitations

The flexure strength of RC beam retrofitted with UHPC in combination with CRFP will be investigated. The properties will be studied according to ASTM - 318 standards. The study does not incorporate testing of specimens at elevated temperature for durability assessment.

The major limitation of this study is the dimension of beam length to be restricted to 1 meter, as UTM machine being used can test maximum length of this size of beam specimen. Due to testing limitation in UTM machine, four-point loading configuration has been adjusted accordingly.

1.5 Brief Methodology

Following the literature review, an experimental study comprising 12 x RC beams has been conducted. The beams of (1000 x 175 x 150 mm) were casted with normal strength concrete (NSC) of 3000 psi. Beam along with its cylinders were cured for 28 days for compressive strength of concrete. After testing at ultimate (100%) and 75% loading, strengthening of beams was done using UHPC layer in combination with CFRP. The mix design for UHPC as reported by Sohail et al. [10] was followed. Whereas CFRP sheet having superior tensile strength (MPa), youngs modulus (GPa), Elongation %, coefficient of thermal expansion has been used. For adhesives and fillers; Epoxy resins having good bond strength and resistance were chosen.

1.6 Novelty of the Work, Research Significance, and Practical Implementations

The researchers across the globe are proposing new techniques for strengthening and retrofitting of RC elements. CFRP has been reported to be an expensive solution in many cases of structural rehabilitation whereas, cement-based repair compatible with the existing concrete is low-cost solution. As very few studies have been conducted on strengthening of severely damaged beams using combination of UHPC layer with CFRP laminate therefore, this research is an attempt to provide a solution to introduce a retrofitting technique which can even be used for severely damaged beams (100% loaded) beside durability and sustainable alternatives. This effort is also extremely important for the development of construction industry in

Pakistan as well because locally available material will be used for preparation of UHPC.

1.7 Thesis Outline

This thesis includes five chapters. That are:

Chapter 1 is an introductory which covers the background, research motivation, problem statement, and overall / specific aims of this research, scope of work with study limitations, brief methodology, and thesis outline.

Chapter 2 consists of the literature review. It comprises of background, nature of new strengthening materials and their properties, studies conducted on use of these materials and their effect on performance of RC beams.

Chapter 3. This chapter describes the experimental scheme of thesis including selection of materials for NSC and UHPC, mix design, casting of specimens, testing, and summary.

Chapter 4 includes the results obtained from tests and their analysis. The results have been analyzed after studying the failure pattern and compared with control beam as well as individual beams. The results project the increase in strength of RC beams.

Chapter 5 consists of conclusions and future recommendations.

Chapter 2

Literature Review

2.1 Background

Concrete is regarded as the most significant building material, with its usage always rising across the globe. However, cconcrete has low tensile strength and weak resistance to crack opening and propagation, which makes it a relatively brittle material [11]. This property of concrete when coupled with aging, change in loading condition, design faults and alteration in intended use makes the RC structure susceptible to failure. Therefore, strengthening of RC structure or element is necessitated to continue its serviceability for intended purpose.

The strengthening of structures using traditional concrete suffers high reinforcement costs and it is a complex process taking long periods. Researcher over the years have studied new reinforcement materials bearing in mind the aspect of durability and sustainability. These materials mainly include high strength concrete (UHPC), fiber reinforced polymer (FRP) and cementitious composites [12]. Each material mentioned above has its advantages and disadvantages depending upon strength to weight ratio, compatibility between the parent and repair material, corrosion, durability and failure modes. Furthermore, composite strengthened methods are increasingly being explored to optimize the efficiency and full utilization of the characteristics of these materials.

2.2 Fiber Reinforced Polymer (FRP)

Fiber rreinforced polymer is a composite material consisting of a polymer matrix reinforced with fibers, typically made of carbon, glass, basalt, or aramid. Due to its noncorrosive and nonconductive qualities, it has obvious advantages over steel reinforcement. Therefore, FRP composites have been used for a long time as a replacement material to create reinforcing bars for reinforced concrete structures. Overall, the types and application of FRP composites is shown in Figure 2.1. In 1975, FRP was first used in Russia as reinforcement bars. In the 1980s, European investigations explored using FRPs as a reinforcing bar for bridge restoration and strengthening, while FRP composites were used in the United States for 25 years. In 1996, the Japanese team introduced design guidelines for FRP for strengthening reinforced concrete structures, leading to its exponential expansion and worldwide design supervision [13]. FRP reinforcements' characteristics depend on factors like fiber volume, fiber type, resin type, orientation, and quality control. Glass fibers are cheaper but less durable due to alkali sensitivity. Carbon fibers offer better resistance, are insensitive to chloride ions, and have better fatigue strength. Carbon fibers are more favourable due to their resistance to high temperatures and ultraviolet rays.

The durability of FRP reinforcement is influenced by its component properties and interface between components. Long-term properties of FRP include durability, creep rupture, and fatigue. Alkali environment and moisture access in concrete affect durability, whereas creep rupture occurs when FRP fails under constant load [14] [15]. Ortiz et al. [16] noted that advancements in FRP materials have led to improved mechanical properties, making them comparable to steel. Furthermore, long-term degradation models indicate that GFRP bars can retain about 70% of their tensile strength over a service life of 100 years. In 2020, a hospital building in Rawalpindi (Pakistan) has been retrofitted using CFRP in beams and columns along with concrete jacketing as shown in Figure 2.2. Chen et al. [17] examined that durability of CFRP and GRFP reinforcing bars exposed to various conditions, including water, alkaline pore solutions, saline, and chloride ions. The aging process was accelerated using elevated temperatures and various cycles. The GRFP bars showed a significant loss in strength; both open and embedded FRP

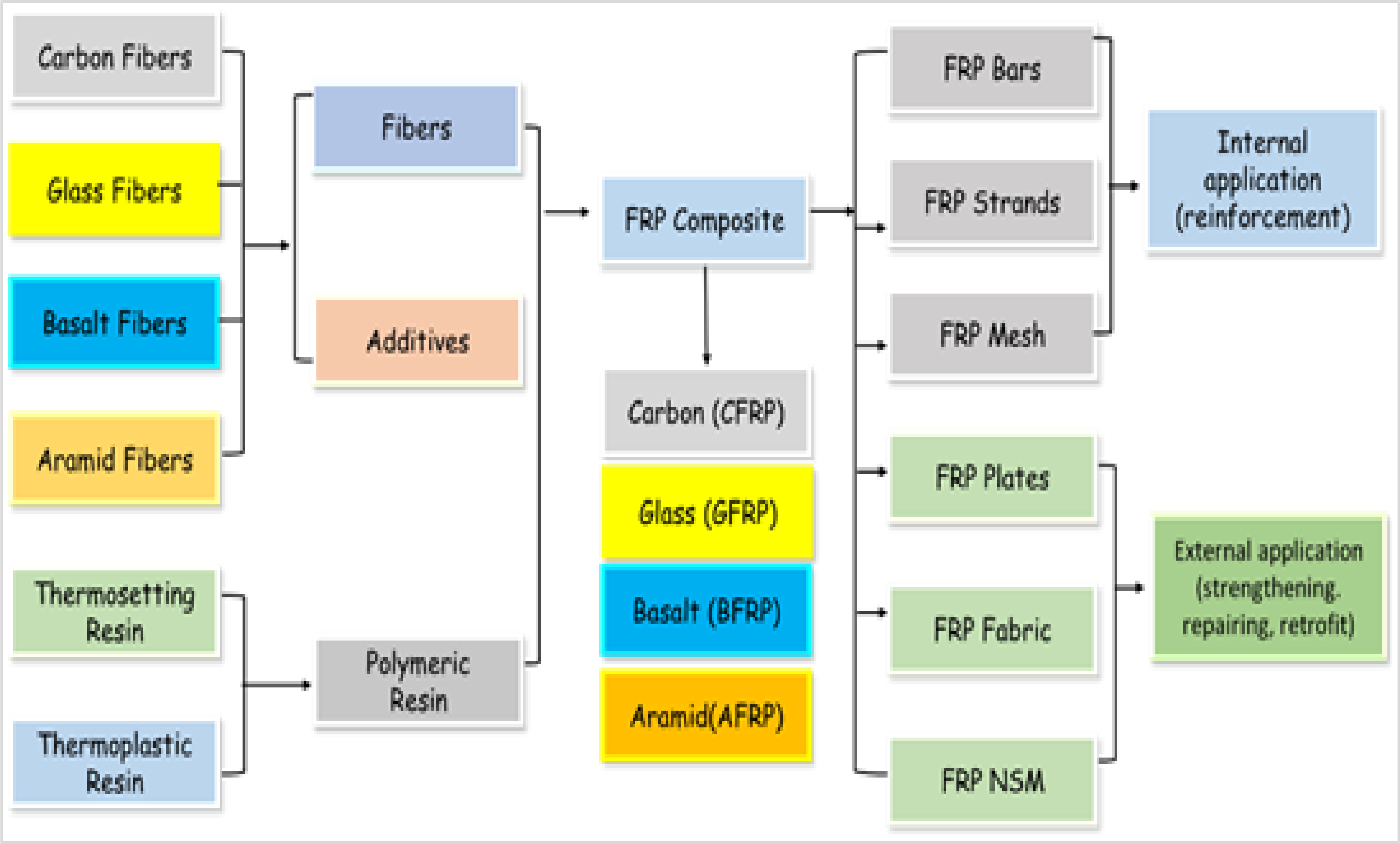


FIGURE 2.1: Types and application of FRP composites [16]

Figure 2.2: CRFP used to repair beams in a hospital at Rawalpindi Pakistan

bars, especially at 60C. However, CFRP bars showed excellent durability.

2.3 Ultra-High-Performance Concrete (UHPC)

The development in concrete has been ongoing since long until in 1960, when concrete with compressive strength upto 800 N/mm 2 was developed under laboratory conditions. In 1980, the concept of creating fine-grained concrete with a very dense and uniform cement matrix to stop the formation of microcracks was presented and the term high performance concrete came to be known [18]. In 1981, Hans Hendrik Bache identified vital rules for ultra-high strength concrete. Based on these rules, in 1985 Richard and Cheyrezy introduced the commercial UHPC product Ductal by Lafarge [19]. UHPC is a high-strength, ductile, and durable cementitious material and can be treated as combination of self-compacting concrete (SCC), fiber reinforced concrete (FRC) and highs-performance concrete (HPC) as shown in Figure 2.3 [20]. New developments in UHPC are a continuing process.

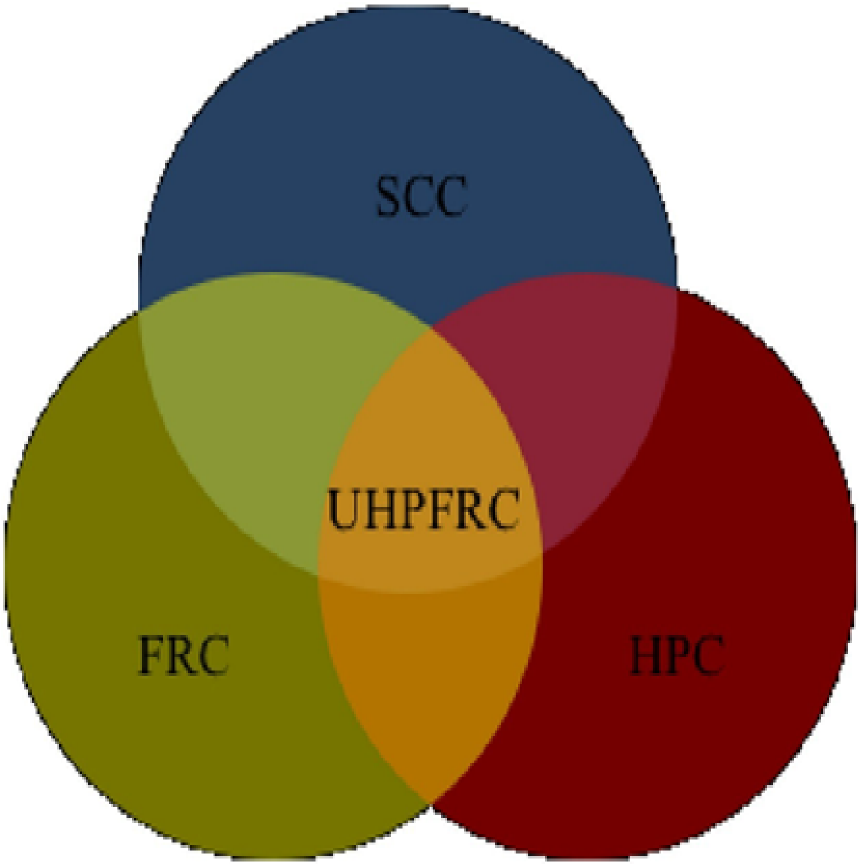


Figure 2.3: Types of UHPC [20]

The countries like USA, France, China and Japan etc., have framed relevant standards and specifications on design, testing, and applications of UHPC. However, the definition of compressive, flexural, and tensile strengths of UHPC varies across different countries and regions due to variations in materials and sample sizes [21]. As per report published by Federal Highway Administration US [22] , over 50 bridges in US / Canada, 24 in Europe and 27 in Asia / Australia were repaired using UHPC. Few of pictures of bridges repaired with UHPC are shown in Figure 2.4.

Figure 2.4: Reapir of Bridges with UHPC (a) Mars Hill Bridge, Wapello County, IA (b) Sakata-Mirai bridge, Sakata, Japan (c) Pedestrian bridge, Sherbrooke, Quebec, Canada [22]

2.3.1 Basic Principles of UHPC

The basic principles of UHPC design focus on optimizing its composition and microstructure to achieve superior mechanical properties. These principles include [23]:

- Improve homogeneity of the mixture by using very fine aggregates to improve packing density.

- To make dense microstructure to minimize porosity by careful selection of material and mix design.

- Use of fibers to withstand stresses and act as micro-reinforcement within mix.

- Low water to cement ratio, typically less than 0.2.

- Use of superplasticizer to enhance workability.

2.3.2 Mechanical Properties of UHPC

The experimental findings have shown that UHPC has shown excellent mechanical properties for use as a construction material. High compressive strength being main mechanical property of UHPC is an indication of other mechanical properties including durability. The compressive strength of UHPC is considered greater than150 MPa while few researchers have stated it being greater than 120 MPa. The tensile strength ranges from 7 to 15MPa and it can be considered as 1/10th of compressive strength of UHPC [24]. The flexure strength is greater than 30 Mpa depending upon 28 days or high temperature curing regime. Irrespective of the high strength value of UHPC, these are mainly due to packing of material constituents, low water -binder ratio, mix design and curing method [25]. Table 2.1 shows the studies done on mechanical properties of UHPC.

Table 2.1: Studies on Mechanical Properties of UHPC

S. No.	**Mechanical Property**	**Paper Title**	**Conclusion**	**Reference**
1	Compressive	Ultra-high performance fiber-reinforced concrete. Part I: Developments, principles, raw materials	Ccompressive strength ranges from 150-200 MPa. Fiber ratio improves the ductility of concrete with an optimal fiber content of 2%.	Akeed et al. [26]
2	Tensile	Hybrid effects of steel fiber and microfiber on the tensile behaviour of UHPC	Upto 22 Mpa. Increasing the fiber volume increase the direct tensile stress and energy absorption capacity.	Kang et al. [27]
3	Shear	Shear Tests for Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) Beams with Shear Reinforcement	Shear strength is 10-15 Mpa. The shear strength of UHPC/UHFRC depend on fiber ratio, shear reinforcement and slenderness	Lim, W.Y, and Hong,S.G [28]
4	Toughness and Flexure	Mechanical Properties of Ultra High-Performance Concrete	25-60 MPa, Linear relationship was observed for Flexural and Split tensile strength (28 days age)	Prem et al. [29]
5	Elastic Modulus	Experimental investigation and prediction of elastic modulus of ultra-high performance concrete (UHPC) based on its composition	35-60 Gpa. Most important factor affecting elastic modulus of UHPC is water binder, followed by other constituents.	Quyang et al. [30]

2.3.3 Durability of UHPC

Researchers over the years have propagated excellent durability properties of UHPC. A mix design of UHPC using recycled glass powder or fly ash can achieve high compressive strengths exceeding 176 MPa with both materials showing strain-hardening behavior under direct tension and excellent electrical surface resistivity of over 870kcm [31]. Zhong Rui, et al. [32] reported that durability of micro-cracked UHPC displayed excellent resistance to freeze-thaw and chloride showed up to 200 cycles but weakened after 300 cycles. Similarly, Wenjie et al. noted that UHPC using design mix of industrial waste, sea and manufactured sand showed excellent strength and durability properties including impermeability, free and thaw and chloride resistance [33]. UHP-ECCs have excellent corrosion resistance in harsh environments and extremely low permeability to liquids, gases and ions [34].

Similarly, Sohail et al. [10] stated that HPC and UHPC is feasible and practical solution for durability issues faced during harsh climate. UHPC can be made using common available material, conventional mixing and curing to achieve compressive strength of 160 MPa. The study concluded that UHPC displayed dense microstructures, high electrical resistance, negligible chloride permeability, low sorptivity, no carbonation. Creep of UHPC is much less than conventional concrete. This results in reduced prestress losses but can be detrimental if relied on to reduce stresses in restrained members. UHPC has sufficient fatigue resistance in both tension and compression to resist several million cycles of loading. Its impact strength is two to three times higher than its static strength [3]. The homogenous microstructure, low permeability and porosity of UHPC, enables it to resist freeze and thaw cycles of 400500 and wetting-drying cycles of 4500 without any degradation [35].

2.3.4 Rheology of UHPC

The rheological properties of UHPC are critical for its successful placement, consolidation, and performance. It is distinguished from other concrete types by its unique rheological properties. Research indicates that UHPSC show a lower yield

Table 2.2: Different Mix Designs of UHPC reported in Literature

S. No.	**Material (kg/m3)**	**Larfarge Ductal [20] [38]**	**CRC Aalborg [20] [38]**	**CEMTEC [22]**	**Cor-Tuf US Army [39]**	**Sohail et al. [10]**
1	Cement	712 (28.5%)	861(34%)	1050 (36%)	790 (31%)	820(34%)
2	Fine Sand	1020 (40.8%)	792(31.2%)	514(18%)	765(30%)	1038(42%0
3	Silica Fume	231 (9.3%)	215(8.5%)	268(9%)	308(12%)	190(8%)
4	Fly Ash	-	-	-	-	150(6%)
5	Quartz	211 (8.4%)	-	-	216(9%)	
6	HRWR	30.7 (1,2%)	9.4 (0.4%)	44 (1.5%)	14(1%)	25(1%)
7	Accelerator	30 (1.2%)	-		-	
8	Water	109 (4.4%)	220(8.8%)	180 (6%)	166(7%)	173(7%)
9	Fiber	156 (6.2%)	218(8.6%)	858(29.5%)	247(10%)	48 (2%)
10	Glass Powder	-	215(8.5%)	-	-	

Table 2.3: International Codes / Standards related to UHPC [39]

S. No.	Code / Standard	Country	Insight
1	CSA A23.1, 2014	Canada	Based on chapter 8, a working group has been set up to develop and study UHPC
2	NF P18-470 2016	France	It covers structural and nonstructural UHPC.A document related to specifications, production and performance of UHPC
	NF P18-710 - 2016		It compliments Euro Code and gives design rules for UHPFRC (both buildings and bridges)
	NF P18-451 - 2018		It gives specific rules for execution of UHPFRC structures, increase knowledge and promote use of UHPFRC
3	ACI committee 239	USA	The committee creates standard for use and design of UHPC as per ASTM C1856/C1856M.
4	ASTM C1856 (M 2017)	USA	Provides procedure to measure properties of fresh UHPC and test specimen of hardened UHPC
5	JSA / KS L511	Japan	These have given standards for concrete materials, including UHPC, focusing on performance criteria and ensuring consistency in quality.

stress and higher plastic viscosity due to enhanced flowability, stability, and resistance to segregation [36]. The use of low water-to-binder ratio (w/b) and high binder content reduce the porosity of the matrix which makes UHPC to exhibit higher mechanical properties and increased durability. Therefore, material selection and mix design are very important stage which can help to effectively control the rheological properties of UHPC [37].

2.3.5 Mix Design of UHPC

Different mixture design methods have been developed based on trial tests and empirical reference values which have resulted in varying characteristics and applicability due to their different principles [21]. The different mix design developed over time and reported in literature are tabulated in Table 2.2. UHPC has very high cementitious material contents and low water-to-cementitious material ratios. UHPC can be mixed in conventional mixers, but its mixing time is longer.

The orientation and dispersion of fibers affect the tensile properties and strength development of UHPC along with methods, duration, and type of curing [3]. After conduct of a detailed overview of microstructural and material properties of UHPC Mishra & S.P Singh [35] suggested optimum value of water binder as 0.18-0.22, fiber contents as 1-2% and HRWR as 1.5-2.4%.

2.3.6 UHPC Standards

There are no code or standard for UHPC materials which necessitatee development of new standards to to guide structural engineers in designing of UHPC structures. To-date, only technical guidelines and professional recommendations are available to assist in development and design of UHPC as shown in Table 2.3 [23].

2.4 Engineered Cementitious Composites (ECC)

ECC was developed by Li Victor C. in 1993 at the University of Michigan, is a class of HPFRCC based on fiber-matrix bond micromechanics. ECC is a family of materials with varying tensile strengths, ductility, and functionality depending upon specific structural demands [40]. Generally, ECC is composed of cement, quartz sand, fly ash, fibers (1 - 3% by vol), water and HRWRA. The mechanical properties of ECC can be modified by modifying the selection of ingredients to improve the microstructure of ECC. [41]. As design mix of ECC does not include coarse aggregates but addition of polymeric fibers (discontinuous) enable ECC to exhibits high ductility [42].

2.5 Structural Strengthening of RC Beam

2.5.1 Definition of Structural Strengthening

Strengthening refers to repair, retrofitting, and rehabilitation techniques, each with distinct functions and attributes. Repair aims to maintain aesthetic appearance without significantly increasing the performance whereas retrofitting significantly improves the performance of structure like flexure, shear, ductility, service life, and fatigue life. Rehabilitation on the other hand, restores strength or performance lost due to distressing factors [43].

2.5.2 Strengthening of RC Beam

Reinforced concrete beams are crucial element to transfer loads. Therefore, these should be designed for safety and serviceability bearing in mind the adverse conditions like design errors, construction errors, material deficiencies, operational errors, and adverse environmental factors. These factors can adversely affect the performance of beams leading to failure. Therefore, strengthening these beams is essential to improve load carrying capacity and in-service performance. Over the past four decades different strengthening techniques have been developed to improve structural performance of beam which include externally bonded steel plates, concrete jacketing, FRP laminates or UHPC / ECC overlay.

2.6 Performance of RC Beams Strengthened with UHPC and FRP

2.6.1 Flexural Performance

Ahmad S. et al. [8] conducted an experimental and analytical study on flexural performance of pre damaged reinforced RC beams strengthen with different configurations of 30 mm thick UHPFRC jacketing. The study reported that very limited studies have been done on strengthening pre damaged RC beams. The RC beams specimens were initially pre damaged on 30, 75, and 90% of the ultimate load-bearing capacity of control beam. The RC beam with 30% initial damage showed maximum strength enhancement and in terms of configuration three-sided, two-sided, and one-sided strengthening showed the highest to the lowest enhancement in the flexural performance. The results of analytical models developed to predict ultimate load-bearing capacities of beam matched the experimental results. In another study by Martinola et.al [44] the strength of pre damaged beams was increased by using 40 mm thick HPFRC jacket. Alasmar H.A et. al [45] rehabilitated and strengthened damaged reinforced concrete (RC) beams using CFRP and high-strength concrete integrating recycled tire steel fiber. In order to create damaged beams, these were loaded to 80% of their total expected bearing capacity to simulate real-world conditions. The combination of HSC and CFRP increased the capacity of the beams up to 50.3%. In a study by Turki, A. & Al-Farttoosi [46] , the flexural strength of damaged RC beams was examined after strengthening with CFRP. The beams were pre damaged upto 20, 40, 60, and 80%) of the ultimate load. It was concluded that CFRP mounted on near surface performed better and increased the flexural strength upto 57%.

Fayyadh & Abdul Razak [47] assessed effectiveness of CFRP on flexural stiffness of repaired RC beams which were pre damaged to limit of design load, steel yield load and ultimate load. Irrespective of the pre damage level, it was proved that CFRP enhanced the flexure stiffness of the beams. Prem M. et. al [48] studied the flexural behaviour of pre damaged RC beams. The beams were initially pre damaged up to 80 and 90% of ultimate load and then reinforced with UHPC layer

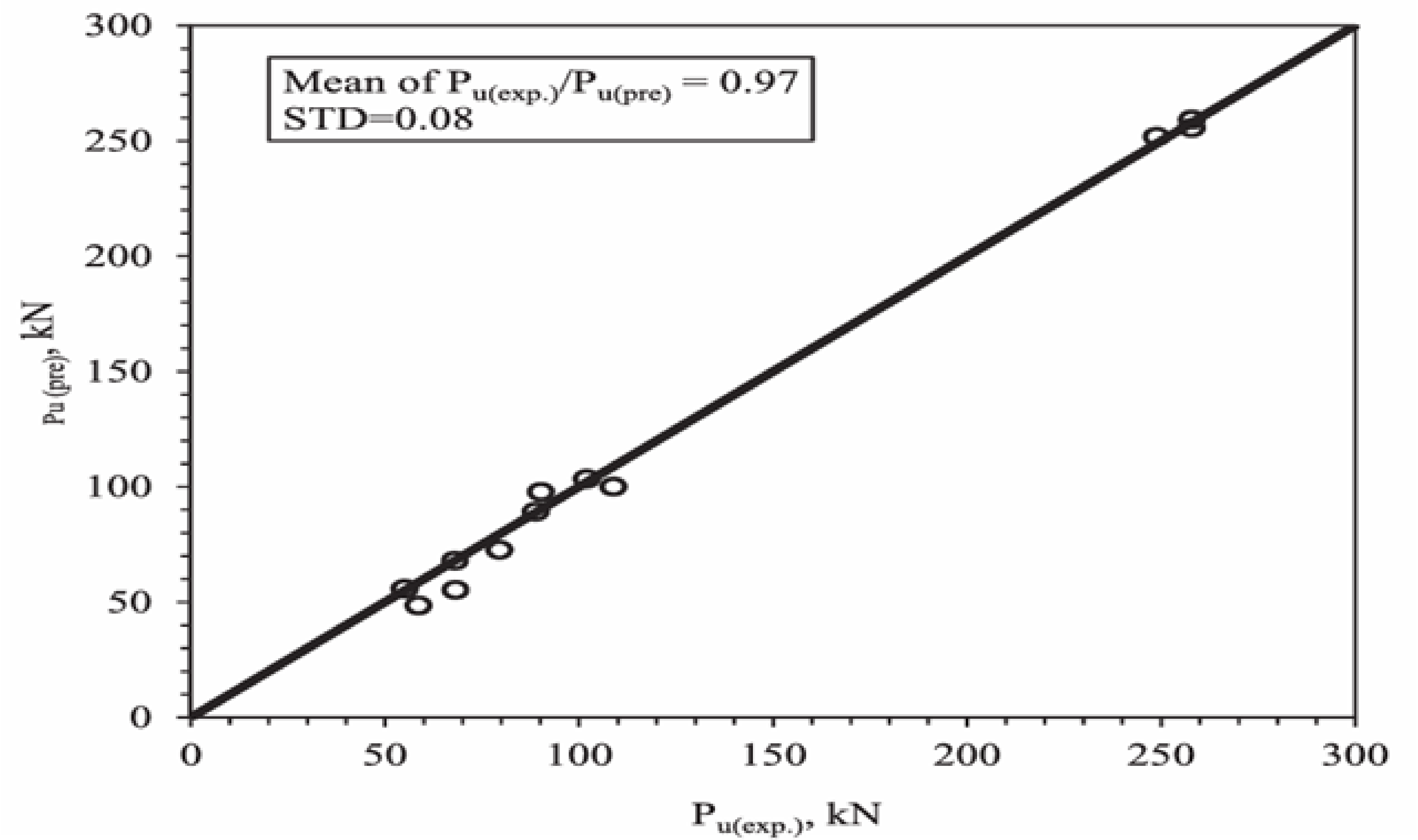


Figure 2.5: Comparison b/w experimental and predicted ultimate loads [44]

on tension side. The result showed an increase in load carrying capacity and ductility of the beams.

Al Osta et. al [49] conducted a study to strengthen corroded reinforced concrete beams using CFRP laminates and UHPC jacketing. The results obtained showed that significant increase in load carrying capacity of the corroded beams The same was validated by analytical model.

Lui Lang et.al [50] analysed the flexural reinforcement effects of the combined use of CFRP bars and UHPC layers on the RC beams. The CFRP bars were embedded in tension zone whereas UHPC layer was placed in the compressive zone. This analysis was based on calculations derived from the load-deflection curve, and results showed the flexural bearing capacity of the beam strengthened by 15.9%.

In an analytical study by Kadhim et al. [51] , FE modeling was done to determine behavior of RC beams strengthened with UHPC-CRFP combination. The performance of beam was increased including ductility and study validated the experimental findings as shown in Figure 2.5. The load capacity Pu was increased from 112% - 463% by varying the CRFP reinforcement ratio. Sequel to analytical study Kadhim et al. [52] , pointed out the lack of research on UHPC reinforced with FRP overlays which calls for investigation on this combination. Using this combination, it was found that the ultimate load bearing capacity of the RC beams strengthened increased up to 183%. This improvement in load capacity was attributed to the effective bonding and reinforcement provided by the CFRP and UHPC materials. The result also showed an increase in ductility up to 2.6 times. Chen Rui et al. [53] conducted study on seven existing RC beams of a 15-year-old bridge after reinforced using GRFP or steel - UHPC overlays. The beams were subjected to in-situ four-point bending tests to estimate the effects of rebar type and reinforcement ratio.

The results revealed that GFRP-strengthened beams showed faster stiffness degradation and wider crack spacing compared to steel-strengthened beams. Also, an increase in reinforcement ratio improved the flexural capacity, stiffness, and cracking resistance. The evaluation of long-term performance and environmental effects

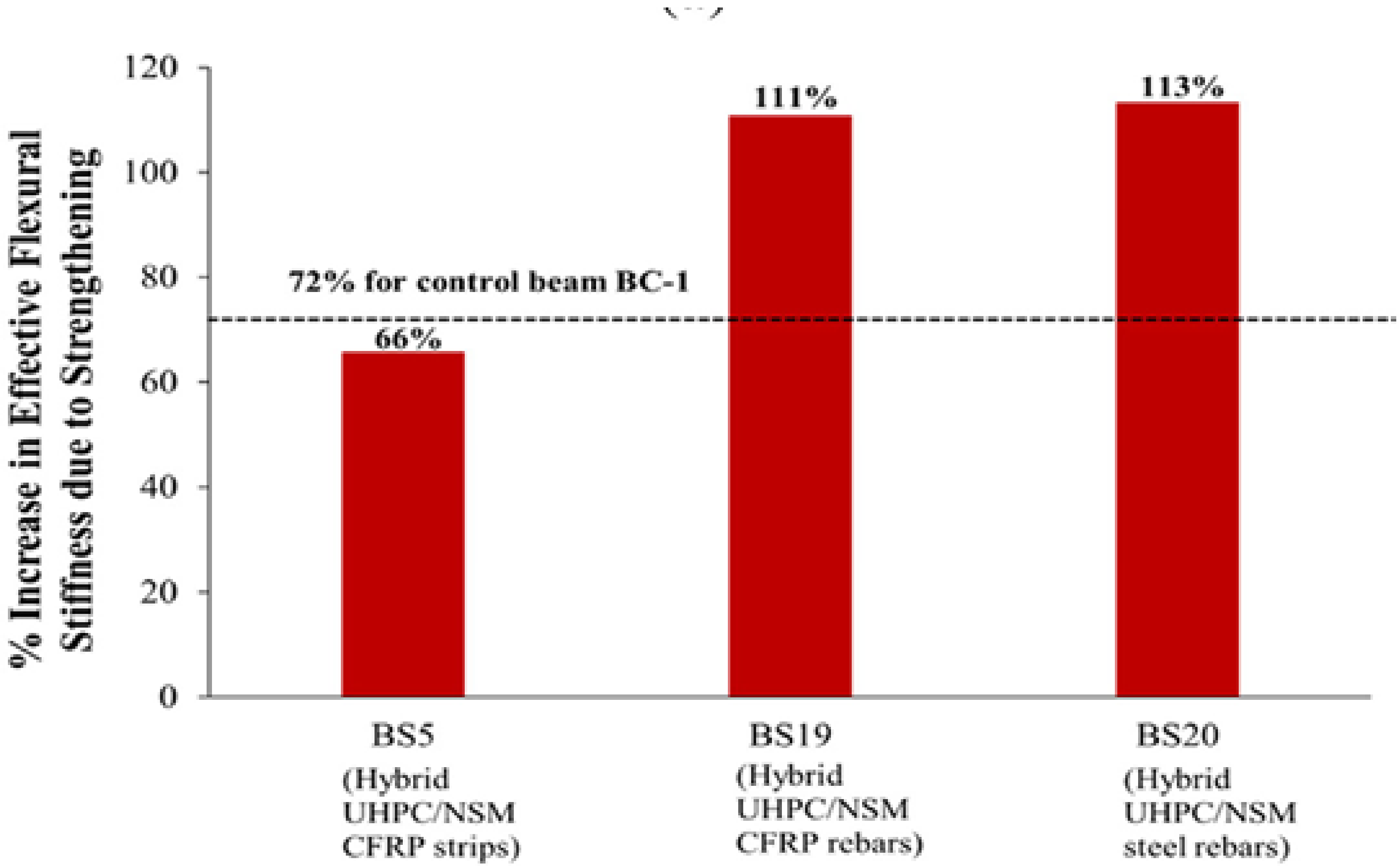


FIGURE 2.6: Comparison of increase in flexural stiffness with different techniques [49]

on the strengthened beams was not addressed in the study. Mao Kuanhong et al. [54] studied the tensile behavior of UHPC and CFRP. The test parameters included grid type, grid size, grid layers and steel fiber content. The results showed that strain hardening occurred due to fiber content greater than 1% and CFRP enhanced tensile stress by 30%. Mukhtar et al. [55] conducted study on strengthening of RC beams with combination of FRC layer and CFRP sheets, The results showed increase in the ultimate load of strengthened beams by 29 - 59% and ductility (twice) compared to FRP alone. The best configuration for maximum load and ductility was achieved with an FRP reinforcement ratio of 0.18% and fiber percentage of 2% in FRC. Also, FRC layer helped to overcome brittle debonding behavior of FRP. Later a finite element model accurately predicted the experimental findings as well.

In another study by Elsanadedy et al. [56] , traditional and hybrid system (UHPC and NSM CFRP) were compared using experiment and FE modeling. Based on findings, it was concluded that hybrid UHPC with NSM CFRP bars or steel rebars can be used to increase flexure stiffness. This is shown in Figure 2.6 as well. Mirdan Dhafer and Abdul Ridah Saleh [57] in a study concluded that UHPC layer on tensile side significantly increased the ultimate load capacity (Pu) of beams by 11% while UHPC layer with construction joint Pu increased by 5%. The study also highlighted that use of steel or GRFP bars in UHPC enhanced the performance, and a brittle failure was observed, with an increase of Pu upto 41%. El-Hacha and Danna Chen [58] carried out study on hybrid GRFP hollow box section beams. These beams were later strengthened with combination of UHPC and CRFP. The results showed higher flexural strength, stiffness and improved bond connection which maintained full composite action till failure.

2.6.2 Shear Performance of Retrofitted RC Beams

Several studies investigated the shear performance of reinforced concrete (RC) beams retrofitted with UHPC overlays with FRP and found out that the beams had an increased shear capacity compared to the original beams. Nadir Wasim et al. [59] proposed a hybrid retrofit technique for RC beams deficient in shear, using FRP-reinforced UHPC overlay. Based on experimental data, an analytical model was also developed to predict shear capacity of beam by modifying existing code equations to include the contribution of UHPC overlay to shear. The system increased the beam capacity Pu from 73-117% and resultantly beam failed in flexural rather than shear. Pourbaba et al. [60] compared the flexural and shear behavior of UHPFRC beams with NSC. Results revealed that the experimental flexural and shear capacities of UHPFRC specimens are up to 3.5 times greater than their NSC. Another study by Rui and Qi Hou [61] determined that the shear strength of UHPC beams with steel fiber is improved to a great extent. Steel fibers in UHPC can act in concert with shear reinforcement to suppress shear cracks.

Chuanjing and Hassan [62] stated that UHPC-repaired beams showed significantly reduced lateral displacements under higher impact forces highlighting the promise of UHPC as a strengthening material in this application. Chang Chen, et al. [63] carried out experimental and analytical modeling by strengthening corroded RC beams with UHPC and FRP. It was concluded that shear capacity was significantly increased, and cracks development was controlled. While UHPC controlled the crack widths, FRP enhanced the tensile strength. In a study by Chalioris et. al [64], RC beams were failed in shear (heavily damaged) and then repaired with U-shaped mortal jackets.This study also highlighted that very few studies have been done where beams were repaired after preloaded to cause failure.

2.6.3 Static and fatigue response of Retrofitted RC Beams

The study conducted by Ganesh et al. [65] looked into the static and fatigue characteristics of retrofitted RC beams with GGBS-based ultra-high performance concrete strips (5, 10 and 15 mm thick). A finite element model was developed to predict numerical response of retrofitted RC beams under static and fatigue loads. The study included the parameters of concrete damage, failure criteria, stress-crack relation, and fracture properties. The model correlated with experiments with minimal deviation of 12%, mainly due to porosity, rebar slip, and experimental errors. Similarly, it was reported that the compressive failure of the composite occurred due to the development of localized cracks within the UHPC that caused

Table 2.4: Insight on papers published on behaviour RC beams strengthened with UHPC and FRP

S. No.	**Paper**	**Author**	**Paper Insight**
1	Experimental study on RC beams strengthened in flexure with CFRP-Reinforced UHPC overlays	Kadhim, Majid MA, et al. [52]	The Pu of strengthened beams increased up to 183% with CRFP and UHPC combination. Ductility increased b/w 2.3 2.6 times.
2	Behaviour of RC beams strengthened in flexure with hybrid CFRP-reinforced UHPC overlays	Kadhim, Majid MA, et al. [52]	FE and analytical model validated existing experimental studies. The performance of beam was increased including ductility.
3	An innovative reinforcement method: the combination of CFRP bars and UHPC layer is applied to the flexural reinforcement of RC beams	Lui Lang et al. [50]	A novel method combining CFRP bars in tension zone with UHPC layer in compressive zone to enhance flexural capacity of RC beams, showing a 15.9% increase in strength.
4	In-situ evaluation on existing RC beam strengthened with GFRP-reinforced UHPC overlay	Chen Rui et al. [53]	Seven existing RC beams of a 15-year-old bridge were reinforced using GRFP or steel - UHPC overlays. The results revealed improved flexural capacity, stiffness, and cracking resistance.
5	Hybrid UHPC/NSM CFRP strips vs. traditional systems for flexural upgrading of RC beams Experimental and FE study	Elsanadedy et al. [56]	Comparison of traditional and hybrid UHPC/NSM CRFP method was drawn for flexural performance. It was concluded that hybrid system outperformed.
6	Flexural performance of reinforced concrete (RC) beam strengthened by UHPC layer	Mirdan Dhafer and Abdul Ridah Saleh [57]	UHPC with embedded GRFP bars increased the Pu by 41%.

S. No.	Paper	Author	Paper Insight
7	RC beams strengthened in shear with FRP-Reinforced UHPC overlay: An experimental and numerical study	Nadir Wasim et al. [59]	The beam capacity was significantly increased and failed in flexural instead of shear after strengthening.
8	Shear Strengthening of Corroded RC Beams Using UHPCFRP Composites	Chang Chen, et al. [63]	The shear capacity was significantly increased. Experimental and analytical model supported findings.
9	Behaviour of hybrid FRPUHPC beams subjected to static flexural loading	El-Hacha and Danna Chen [58]	Improved flexural and stiffness performance. The bond connection maintained the composite action till failure.
10	Flexural performance of pre-damaged RC beams strengthened with different configurations of UHPFRC layer-experimental and analytical Investigation	Ahmad S. et al. [8]	Pre damaged reinforced RC beams strengthened with different configurations of 30 mm thick UHPFRC jacketing. The RC beam with 30% initial damage showed maximum strength enhancement with three-sided strengthening. The analytical models matched the experimental results
11	Rehabilitation and Strengthening of Damaged Reinforced Concrete Beams Using Carbon Fiber-Reinforced Polymer Laminates and High-Strength Concrete Integrating Recycled Tire Steel Fiber	Alasmar H.A et al. [45]	Damaged RC beams were retrofitted using CFRP and HSC using recycled tire steel fiber . The combination of HSC and CFRP increased the capacity of the beams up to 50.3%.
12	Strategies for strengthening of corroded reinforced concrete beams using CFRP laminates and UHPC jacketing	Al- Osta et al. [49]	Corroded RC beams were repaired using CFRP laminates and UHPC jacketing. The results showed significant increase in load capacity and was validated by analytical model.

the hoop rupture of the FRP. The confinement efficiency was found to be lower for FRP-confined UHPC compared with FRP-confined NSC and HSC, owing to the ultrahigh strength of UHPC [66].

2.6.4 Insight of Papers Published on FRP & UHPC

At present various papers have been published on behavior of RC beams when strengthened with UHPC and FRP. The insight on some of important papers is given in Table 2.4.

2.7 Summary

Studies show that UHPC and FRP laminates can significantly improve load carrying capacity of reinforced concrete (RC) beams. However, UHPC layer reduced the ability to sustain inelastic deformation before failure. Also, cracks in UHPC reduced its ductility and caused the tensile reinforcement to break prematurely. FRP laminates can effectively improve the bearing capacity of beams but cannot fundamentally solve the issue due to de-bonding in the FRP-concrete interface This is mainly attributed to the weak tensile feature of concrete, where the developed cracks in concrete structures lead to interfacial stress concentrations resulting in de-bonding of FRP laminates. Based on literature review, it is also ascertained that different pre damage levels have been set before retrofitting of beams but very few studies have been done where beams were initially subjected to failure on ultimate load. As far as studies to assess performance of RC beams retrofitted with combination of UHPC and FRP is concerned, still lot of work is needed in terms of its long-term performance, durability issues and effects of environmental conditions. Furthermore, impact of different orientation / configuration of FRP also needs to be studied. Notwithstanding above, it is possible that RC beams can be strengthened with UHPC in combination with various configuration of FRP laminates to further enhance its mechanical properties. Also, UHPC has great potential to act as a transition layer between FRP laminates and concrete to delay or impede interfacial de-bonding and improve the toughness of RC elements.

Chapter 3

Experimental Program

3.1 Background

Several previous studies have reported enhanced performance of RC beam when strengthened with hybrid UHPC and CRFP strengthening systems. Each of these materials participate in strength improvement with their different characteristics. CFRP has higher modulus and tensile strength, where UHPC adheres well with existing concrete and creates composite action. Researchers have endeavored to develop methods to utilize both materials with their most favorable properties. Therefore, in this experimental program a combination of UHPC and CRFP laminate is used to study flexure strength of RC beam after strengthening. This chapter elaborates the material properties of NSC, UHPC and CRFP. The used mix design, casting, and testing matrix employed to conduct the research.

3.2 Raw Material Properties

Locally available ordinary Portland cement (OPC), Lawrancepur sand, steel reinforcement and coarse aggregates have been used for manufacturing of NSC beam specimens. The flexural reinforcement is #4 (Gde 60) and #3 bars (Gde 40) have been used as stirrups. UHPC has been manufactured on site with locally available material as per mix design mentioned in succeeding paragraph. The silica fume, polypropylene fiber (PP) and high range water reducer (HRWR) super plasticizer locally available in the market have been used in UHPC.

3.2.1 Silica Fume

Sikafume MS 610 product has been used as silica fume. It is in powdered form and can be used for high performance concrete. The product has a density of 550-700 kg/m3 and chloride content are less than 1%. As per product data sheet provided by manufacturer, the recommended dosage of this product is 5-15% of cement weight. The product is available in 10 kg bag as shown in Figure 3.1(a).

3.2.2 Super Plasticizer (HRWR)

Sika Visco Crete -3110 as shown in Figure 3.1(b), is a third generation polycarboxylate based superplasticizer. It gives extended slump retention and helps in development of high strength. It is suitable for use with concrete mixes containing silica contents and pozzolanic material like fly ash. This product has also compatibility with other Sika products used for this project. Although higher dosage of this product can be used depending upon mix design but the recommended dose is 0.4 -2% by weight of binder.

(a)
Sika Fume

(b)
HRWR

(c)
PP Fiber

FIGURE 3.1: Raw Material used in UHPC

3.2.3 Polypropylene Fibers (PP)

Sika Fiber as shown in Figure 3.1(c), is high quality micro monofilament polypropylene fiber intended to reduce and control shrinkage and cracks in concrete. It is available in ready to use bags for 1m3 of concrete. The properties of polypropylene Fiber as per product data sheet provided by manufacturer are given in Table 3.1.

Table 3.1: Properties of Sika Polypropylene Fibers (Manufacturer provided)

Length	**Diameter**	**Density**	**Tensile Adhesion Strength**	**Elastic Modulus**
12mm	18 microns	0.91 g/ cm^3	300 440 MPa	6 000 9 000 N/mm^2

3.2.4 Carbon Fiber Reinforced Polymer (CRFP)

CFRP are available in different forms depending upon fabric weight (gsm) and uni or bidirectional cloth strength. Due to availability in local market, the XPERT Profibre CW System CFRP (230 gsm, unidirectional) has been used for strengthening of RC beams specimens. The CFRP CW system is shown in Figure 3.2 and data sheet as provided by distributor of XPERT Chemicals in Pakistan is given in Table 3.2.

Table 3.2: Properties of CFRP (XPERT Profiber CW System)

S. No.	**Property (BS 6319)**	**Range**
1	Tensile Strength	>25 MPa
2	Compressive Strength	>60 MPa
3	Flexural Strength	>30 MPa
4	Elastic Modulus	230 -250 GPa
5	Thickness	0.167 mm

3.2.5 Epoxy Adhesive

Base Paste Epoxy, a trawl based, sag-resistant patching compound is used for concrete and other surfaces as shown in Figure 3.2. It is used to provide a smooth surface to CFRP. The compound comprising two components are mixed in a ratio of 1:1 giving a thick grey appearance when wet and white once dry. The properties of epoxy adhesive as provided by manufacturer are as shown in Table 3.3.

Table 3.3: Properties of Epoxy Adhesive (Manufacturer provided)

S. No.	Property	Range
1	Tensile Strength (ASTM D638)	>27 MPa
2	Compressive Strength (ASTM 695)	>70 MPa
4	Elastic Modulus (ASTM 695)	>12000 MPa
5	Shear Bond (AASHTO T-237-73)	25 MPa
6	Heat deflection: ASTM D648	50°C

Figure 3.2: XPERT Profiber CW System and Epoxy Adhesives

3.3 Mix Design and Strengthening Matrix

The RC beam specimen have been casted using NSC of 3000 psi with mix ratio of 1:2:4, while UHPC has been used as per mix design of Sohail et al. [10]. The quantity of UHPC required for strengthening of RC beams is 0.099 m^3 (3.5 cft).

Table 3.4: Mix Design of UHPC

		Mix Design by Sohail et al. [10] for 1m^3 of UHPC		**Quantities used for 0.099m^3 (3.5 Cft) of UHPC (kg/m^3) by weight of OPC**
S. No.	**Material**	**kg/m^3**	**Ratio by % weight of OPC**	
1	Cement (OPC)	820	1	80
2	Fine Sand (FS)	1038	1.26	100.8
3	Silica Fume (SF)	190	0.23	19
4	Fly Ash (FA)	150	0.18	15
5	HRWR	25	0.03	2.5
6	Water	173	0.21	17.3
7	Fiber	48	0.06	4.75

The mix design used for UHPC is given in Table 3.4 in which required quantities of ingredients have been calculated on the basis of percentage weight of OPC. The major difference with mix design of Sohail et al. [10] is sand. In existing study only one type of fine sand is used whereas in case of reference mix design of UHPC two types of sand particles were used.

3.3.1 Geometry of Specimen Beam and Casting

The geometry and reinforcement of the sample beam has been illustrated in Figure 3.3. The beam has been casted with a strength of 3000 psi. The beams have rectangular shape with dimensions of 1000mm length, 150 mm width and 175 mm depth and designed as tension-controlled sections following the American Concrete Institute (ACI) codes ACI CODE-31819. The above-mentioned dimensions of the

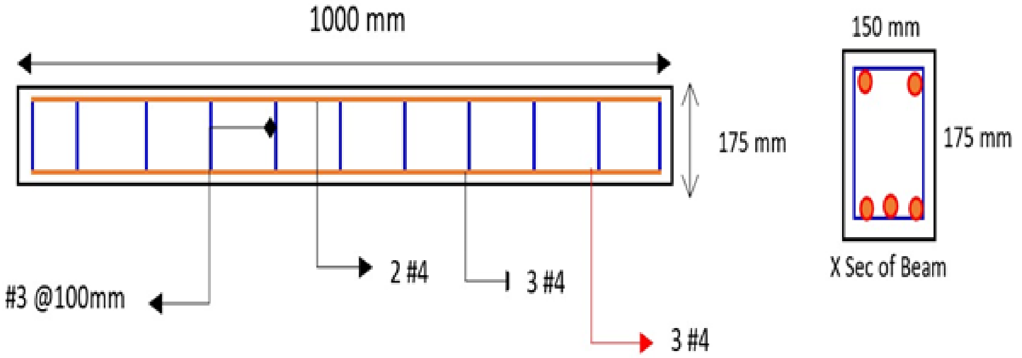


FIGURE 3.3: Geometry and reinforcement of 12x Specimen RC Beam

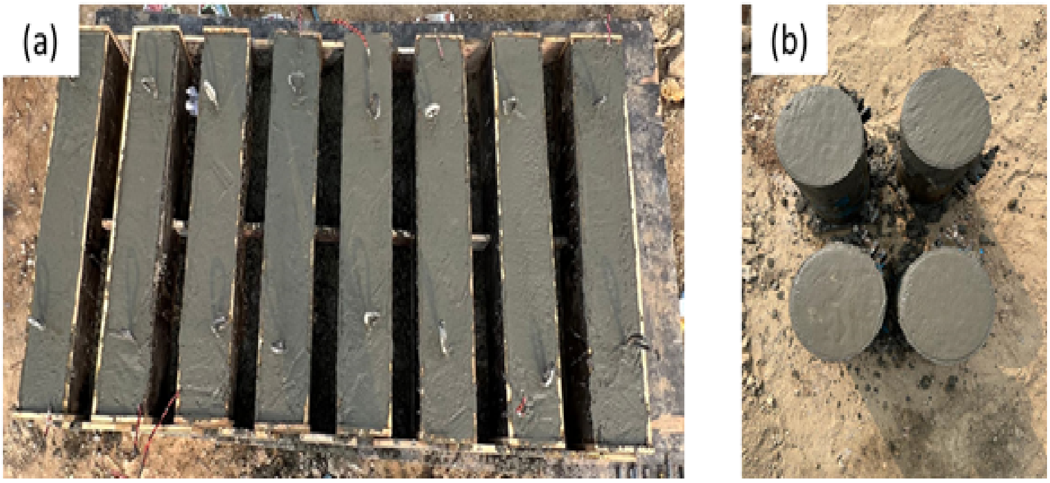


FIGURE 3.4: Casting of specimen RC beams and Cylinders (a) RC beams (b) Cylinders

beam have been used to ascertain actual behavior of beam under four-point loading and deflection. Also, the length has been kept as 1000 mm due to the limitation of available UTM machine at CUST i.e., 1m span between externals supports. The beam was reinforced with 5 #4 flexure reinforcement bars whereas 9 x stirrups were provided using #3 bars with spacing of 100 mm. The reinforcement has been provided with minimum concrete cover of 50 mm and 25 mm on longitudinal and lateral side respectively. 12x beams for flexural analysis as shown in Figure 3.4 (a) along with cylinders were casted for compressive strength as shown in Figure 3.4(b). (a) along with cylinders were casted for compressive strength as shown in Figure 3.4(b).

3.3.2 Strengthening Scheme of Specimen RC Beams

Twelve (12) specimen RC beams having compressive strength of 3000 psi were used to conduct the testing matrix. The beams were initially pre-damaged up to 100% and 75% of ultimate load. The 75% load condition has been used as it simulates the stresses which a beam may face during its service life. On the other hand, 100% preloading has been used to simulate extreme damage scenarios to better evaluate the effectiveness of strengthening techniques and help in comparative analysis. The strengthening system comprised of two types i.e 30mm UHPC and CRFP on bottom as shown in Figure 3.5 (a) second one was 30mm UHPC with U shaped CRFP wraps at 100 mm interval were attached, as shown in Figure 3.5(b). The steps to implement this strengthening procedure are shown in Figure 3.6 and explained in succeeding paragraphs. Mainly, the strengthening matrix / procedure comprised of three phases as under:

- **Phase 1.** 12x specimen RC beams were casted using concrete mix machine with 3000 psi and cured for 28 days. After curing, 4x beams were kept as control (two each for 100% and 75% loading). While 4x beams were tested at 100% load conditions, other 4x beams were tested on 75% loading before strengthening. The beams were tested in UTM machine at CUST. The nomenclature of specimen beams as discussed above is given in Table 3.5.

Table 3.5: Nomenclature of Specimen Beams for Strengthening with UHPC and CFRP

S. No.	**Beam Nomenclature**	**Loading Condition before strengthening**	**Loading Condition after strengthening**	**Remarks**
1	CB - 1	100%	-	Control Beams
2	CB - 2	100%	-	
3	BB-3	100%	100%	Strengthened with 30 mm UHPC & one layer of CFRP on bottom only
4	BB-4	100%	100%	
5	BU-5	100%	100%	Strengthened with 30 mm UHPC and one layer of CFRP on bottom and in U shape on sides with 100 mm interval
6	BU-6	100%	100%	
7	CB - 7	75%	-	Control Beams
8	CB - 8	75%	-	
9	BB-9	75%	100%	Strengthened with 30 mm UHPC & one layer of CFRP on bottom only
10	BB-10	75%	100%	
11	BU-11	75%	100%	Strengthened with 30 mm UHPC and one layer of CFRP on bottom and in U shape on sides with 100 mm interval
12	BU-12	75%	100%	

BB Beam with UHPC & CFRP on soffit , BU - Beam with UHPC on soffit & U shape CFRP.

- **Phase 2.** Eight damaged pre-loaded (75% and 100%) RC beams as shown in Figure 3.6 (a) excluding control beams were strengthen with UHPC. The reinforcement was exposed from soffit (bottom) by carefully removing the concrete cover maximum up to 30mm, as per detail shown in Figure 3.6(b). After cleaning of exposed surface using hard brush, 30mm UHPC layer is poured in eight beams as per detail shown in Figure 3.6 (c). The curing of beams with UHPC is done for 28 days using hot water.

- **Phase 3.** After 28 days, CRFP layer 0.167 mm thick is applied on the bottom surface of UHPC on 4x beams (BB 3, 4, 9 &10) as per detailing shown in Figure 3.6(d). Whereas 100 mm wide U shape CRFP laminate as per strengthening detailing shown in Figure 3.6(e) is provided on 4x beams (BU 5 ,6 ,11 & 12). Clear spacing between laminates was 100 mm. After 14 days, beams are tested for flexure analysis on 100% loading conditions.

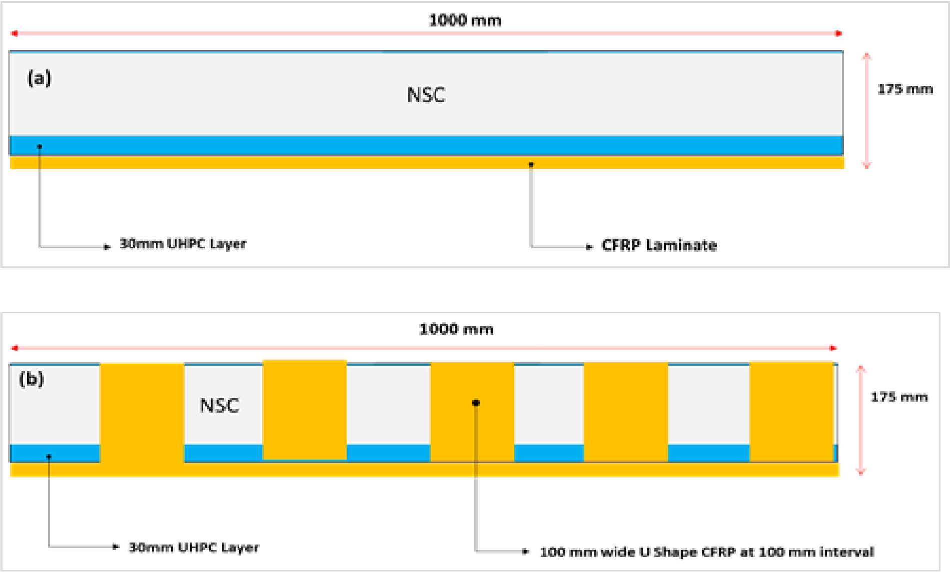


FIGURE 3.5: Strengthening Scheme of Specimen RC Beams (a) Strengthened with 30 mm UHPC and one layer of CFRP on soffit (b) Strengthened with 30 mm UHPC and one layer of CFRP on soffit and in U shape on sides

3.4 Preparation and Application of UHPC

Based on design mix of UHPC, the material for UHPC was selected by weight. After thorough cleaning the mixing machine (capacity half cube meter) of any

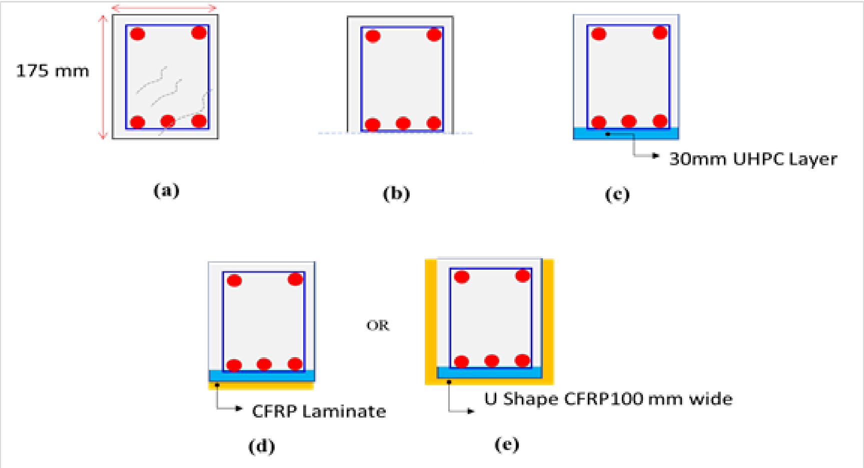


FIGURE 3.6: X - Sec steps for Strengthening of RC Beam with UHPC & CFRP (a) prestressed RC beam (b) concrete cover removed (c) Pouring of 30mm UHPC (d) Fixing of CRFP on bottom side (e) Fixing of CRFP in U Shape on soffit & sides with 100 mm interval

derbies and moisture, dry material less fibers were added in machine. After rotation of machine for 2-3 mins, water and HRWR was added in the bowl. The bowl of mixing machine was set to almost horizontal position to ensure proper preparation of UHPC as suggested by Sohail et al. [10]. Initially, the material got into semi wet cakes which later started breaking and later took the shape of small granular balls as shown in Figure 3.7(a). The balls started breaking after rotation of 45 mins until a fine paste was formed as shown in Figure 3.7(b). Meanwhile, the fibers were added to paste and machine was rotated for another 15 mins. The UHPC was prepared in approx. one hour. As concrete cover had already been removed therefore, 30 mm thick UHPC layer was poured in specimen beams as shown in Figure 3.7 (c). The beams were cured for 28 days as shown in Figure 3.7(d).

3.5 Application of CFRP layer on UHPC

After curing of UHPC for 28 days, the surface of UHPC was smoothened with a sand paper for application of initial layer of adhesive as shown in Figure 3.8(a). As per manufacturer instruction, the epoxy adhesive was mixed with a ratio of 1:1 and was applied with scrapper ensuring that all bubbles are removed. The first layer is kept for 24 hrs to dry up. After 24 hrs, second adhesive layer is applied with a

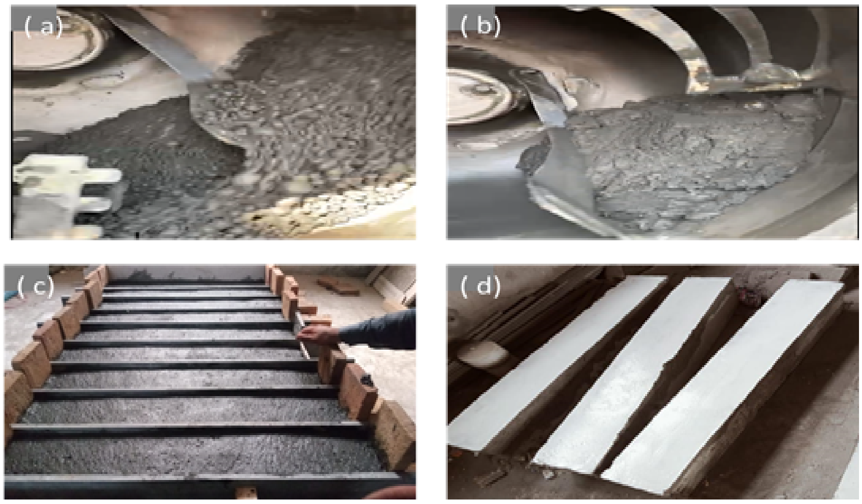


Figure 3.7: Preparation and application UHPC on beams (a) Granular balls developed during initial mixing process of UHPC (b) Development of UHPC paste after 45 mins of mixing(c) Pouring of 30 mm UHPC in Specimen Beams (d) UHPC layer in beams after 28 days curing

mixing ratio of 2:1 by volume using roller. The layer is kept dried for 35 mins to remain it sticky for better adhesion with CFRP layer. As epoxy adhesive is left to dry, CFRP layers are cut into desired length. The CFRP layer was applied to the specimen beams after soaking in solution and fixed with scrapper and roller to ensure no bubbles are left as shown in Figure 3.8(b). The beams were left to dry for 3-4 hrs and then checked for any abnormality. As no abnormality was observed therefore, last roller of adhesive was applied on surface of CFRP and left to dry / strengthening for 15 days for strength evaluation as shown in Figure 3.8(c).

(a)
Smoothening of UHPC
layer with 1st coat of epoxy

(b)
Application of Adhesive
and CFRP laminate

(c)
Specimen RC beams prepared
with UHPC & CFRP

Figure 3.8: Application of CRFP Layer (a) Smoothening of UHPC layer with 1st coat of epoxy (b) Application of Adhesive and CFRP laminate (c) Specimen RC beams prepared with UHPC & CFRP

3.6 Testing Methodology

Concrete is fundamentally strong in compression and weak in tension. Therefore, testing of tensile strength of concrete is important as it gives as insight as to how concrete will behave under bending loads and its tendency to cracks. The flexure strength also known as modulus of rupture determines the tensile strength of concrete. Typically, flexure strength is 10-20% of compressive strength. In order to determine flexure strength of reinforced RC beams with combination of UHPC and CFRP laminate, four-point load test has been conducted using UTM machine. The primary aim of this test set up is to assess the flexural performance of RC beams strengthened with combination of UHPC and CFRP. This test will give an idea as how the strengthened scheme will behave under real time conditions when subjected to bending stresses.

The adjusted four-point load setup on UTM is shown in Figure 3.9. Based on available data load deflection curves and moment curvature curves have been drawn As a result, suitability of strengthening scheme will be determined. The load deflection curves will help determine the stiffness, ductility, ultimate capacity and failure mode of the beam. Whereas, moment curvature curves will enable to understand the local behavior the beam at critical section (midspan) and flexural capacity of the beam. Using the classical equation, the relationship between moment (M) and curvature () has been determined by:

$$\phi = \frac{M}{EI} \tag{3.1}$$

$$\text{Ductility Ratio} = \frac{\phi_u}{\phi_y} \tag{3.2}$$

The ACI 318 code does not mention any specific minimum curvature ductility factor however, it stresses upon ensuring a ductile behaviour of beams where it fails by steel yielding before concrete crushing. Studies have been done which provide a guideline on factors influencing curvature ductility in reinforced concrete beams but very few have mentioned minimum curvature ductility ratio which should be greater or equal to two (>2) [67] [68].

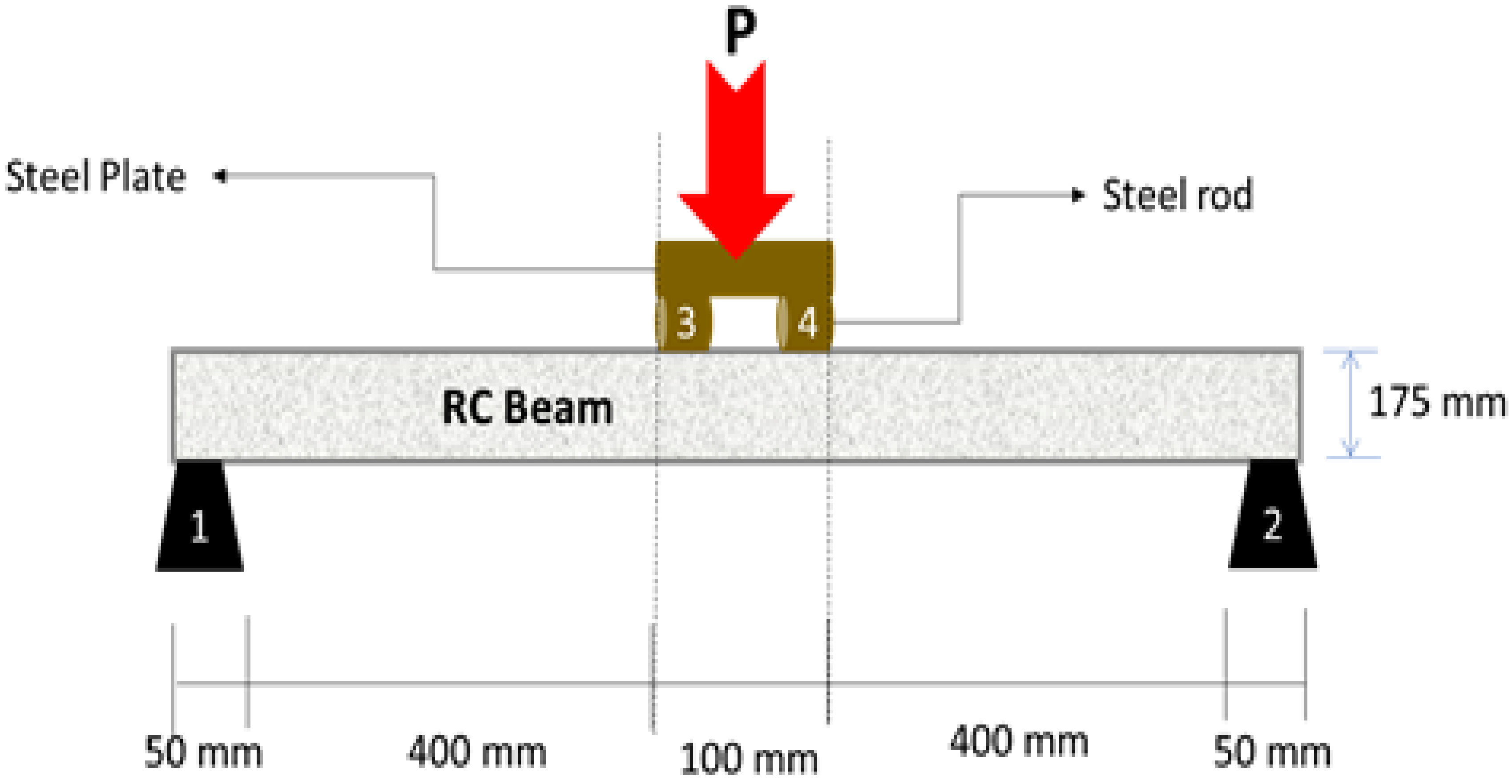
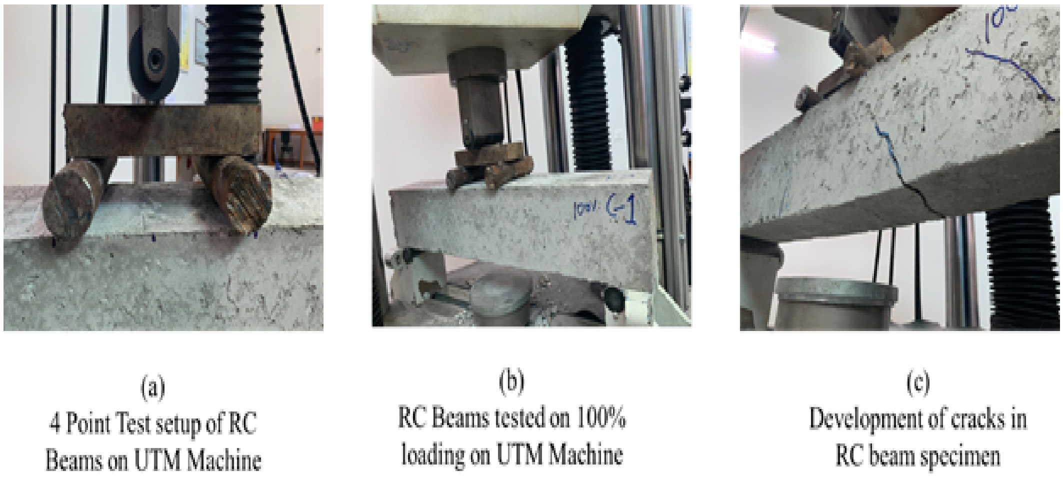


FIGURE 3.9: Four Point Load Set up on UTM

3.6.1 Testing of Control RC Beams Specimen

The control RC beams specimens (CB-1, 2, 7& 8) were tested by using UTM. The deflection control force was applied at a rate of one mm per second. Detailed analysis of results is given in Chapter 4 whereas as, conduct of test for beams (CB-1 &2) subjected to 100% loading is shown in Figure 3.10. Similarly, RC beams specimens (CB-7 & 8) were tested on 75% load of ultimate load taken earlier by CB-1 & 2.


(a)
4 Point Test setup of RC Beams on UTM Machine

(b)
RC Beams tested on 100% loading on UTM Machine

(c)
Development of cracks in RC beam specimen

Figure 3.10: RC Beam Specimen tested on UTM with 100% Loading

3.6.2 Testing of beams strengthened with UHPC & CFRP

The eight specimen beams (BB 3, 4, 9,10 and BU 5, 6 ,11,12) after initial test were un loaded from UTM and were strengthened with UHPC and CFRP combination as per scheme mentioned in 3.3.2. After curing of UHPC (28 days) and CFRP (14 days), the strengthened beams were tested for flexure on UTM machine by applying load of 1mm per second. The results duly recorded are analyzed in Chapter 4.

3.6.3 Testing of UHPC Specimen

Two UHPC specimens of the size 300 mm x 50 x 50 mm were tested to determine compressive strength of UHPC. The compressive strength of UHPC sample was tested and reported as 106.14 Mpa.

Chapter 4

Results and Analysis

4.1 Background

The results have been formulated as real time failure modes of controlled and strengthened beams. The comparison of results has been ascertained based on load-deflection curves and ultimate strength of specimen beams.

4.2 Behavior of Loaded Beams before Strengthening

A total of twelve (12) beams of size 1000 mm x 175 mm x 150 mm were casted with compressive strength of 3000 psi. While keeping two controlled beams tested on 100% load conditions, four beams were tested on 100% loading for strengthening with combination of UHPC and CFRP as discussed in preceding para 3.3.2. Similarly, two beams were kept as control beams for 75% load conditions while four were to be strengthened with combination of UHPC and CFRP after pre loading on 75% load. All the beams were tested under four-point loading at constant rate of 1mm / min. During loading, each beam showed its own behavior, crack propagation and failure mode. The Table 4.1 presents the physical observation recorded during testing in terms of crack pattern and deflection till the point beam started

Table 4.1: Physical Observation and load taken by beams before strengthening

S. No.	Beam	Load on First Crack (KN)	Load on Additional Cracks (KN)			Ultimate Load (KN)	Deflection (mm)	Time (S)
			2nd Crack	3rd Crack	4th Crack			
1	CB - 1	9.58	30.39	51.38	59.09	64.29	8.2	610
2	CB - 2	8.42	24.35	48.64	55.64	62.55	8.17	505
3	BB-3	7.58	29.98	49.41	57.37	61.36	8.58	501
4	BB-4	8.78	23.94	47..58	49.06	53.75	8.45	504
5	BU-5	6.16	28.86	48.06	50.46	58.04	8.356	552
6	BU-6	7.67	26.096	36.86	51.08	62.12	8.338	390
7	CB - 7	9.13	22.04	39.94	47.55	47.55	4.742	265
8	CB - 8	8.38	19.06	28.02	47.55	47.55	4.553	271
9	BB -9	7.56	24.81	32.89	47.55	47.55	4.57	269
10	BB-10	9.08	22.75	31.66	47.55	47.55	4.26	273
11	BU-11	7.802	25.78	30.47	47.55	47.55	4.502	269
12	BU-12	6.31	20.18	28.59	47.55	47.55	4.794	264

taking no further load.

4.2.1 Behavior of Beam on 100% Pre-loading

In control beam CB-1, the initial cracks appeared at 9.58 KN due to uneven surface of beam as shown in Figure 4.1(a). Later, as load was increased, the cracks started travelling from tension zone to the compression zone at 30.39 KN of load. At certain point beams stopped taking further load however, the cracks appearance and deflection was noted. The yield load taken by CB1 was 59.09 KN and ultimate load of 64.29 KN in 610 seconds with a deflection of 9.58 mm. The crack at the bottom face along compression zone was noted as 11mm. As CB -1 started taking no further load, the beam was unloaded from UTM. As far as CB -2 is concerned, the initial cracks were observed at 8.42 KN whereas, yield load was 54.64 KN. The ultimate load taken by CB 2 was 62.55 KN in 505 secs with maximum deflection noted as 8.46 mm. The crack pattern was similar to CB -1 starting from tension zone to the compression zone as shown in Figure 4.1(b).

FIGURE 4.1: Behaviour beams specimen under 100% initial loading (a) CB-1 (b) CB- 2

The crack along bottom face was noted with a width of 10.2mm. Similarly, BB-3, BB-4, BU-5 and BU-6 were put under test at 100% loading to develop cracks and stresses in beams for carrying out strengthening with combination of UHPC and CFRP. The graphical summary of yield and ultimate load taken by beams subjected to 100% loading is shown in Figure 4.2.

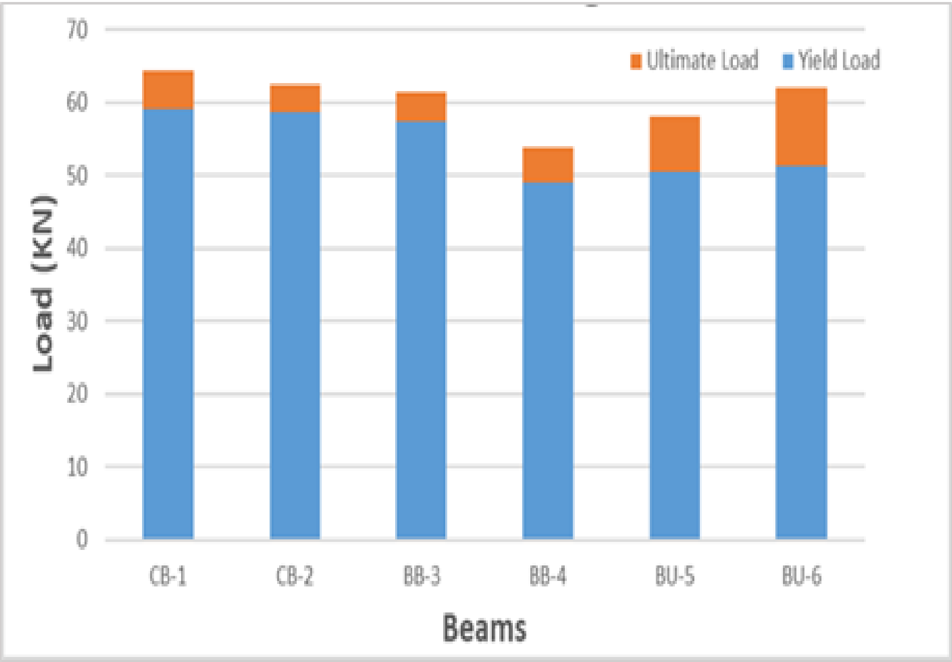


Figure 4.2: Yield and Ultimate load of beams before strengthening

4.2.1.1 Load Deflection Relationship

The load-deflection curves showed a linear trend in the early loading phase indicating elastic behavior, followed by a gradual transition into the nonlinear range where plastic deformation occurred. The load deflection curves of CB-1, CB-2 and BB-4 had same pattern where up to elastic limit the load and deflection showed a linear relation with minor cracks. After that the beams made a soft peak followed by progressive drop in load as the cracks started to widen. The load deflection curves of BB-3, BU-5 and BU-6 had almost symmetrical pattern in which after taking yield load, the curves took a sharp dip and started taking load again. This phenomenon can be attributed to could be due to machine slippage, appearance of local crack leading to quick loss of load capacity. The rise of load after sharp dip indicate that beams redistributed their internal stresses enabling it to resist more load. This is desirable from ductility aspect because beam exhibited enough warning before collapse. In case of BB-4, the deflection curve had same pattern as of CB-1 and CB-2. The load deflection curves of beams loaded on 100% load setup is shown in Figure 4.3.

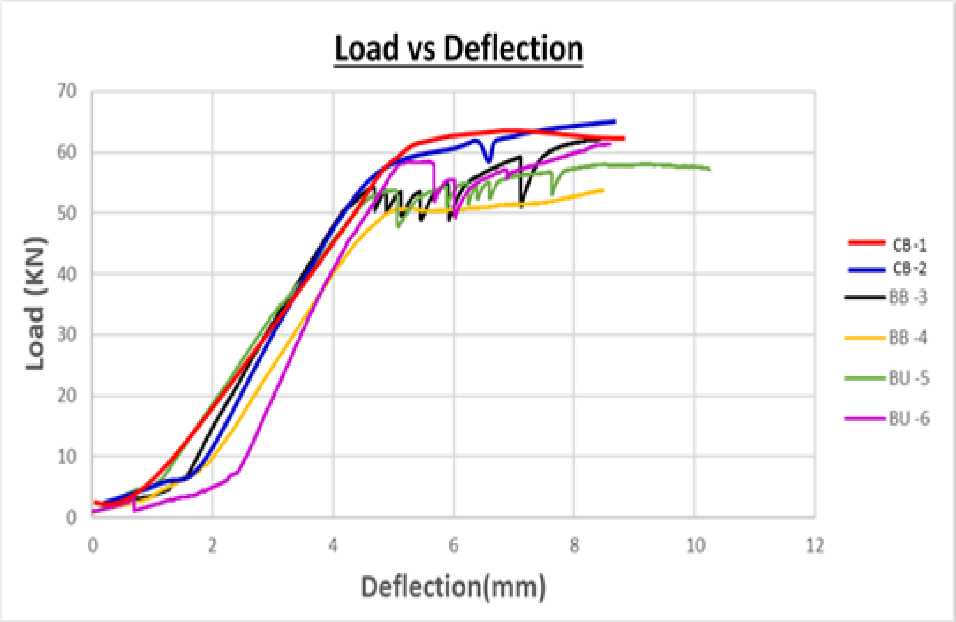


FIGURE 4.3: Load Deflection Curves of beams before strengthening tested on 100% loading

4.2.1.2 Moment Curvature Relationship

Using the classic equation 3.1 and 3.2, moment and curvature were calculated and tabulated in Table 4.2 whereas, Figure 4.4 graphical represents the moment curvature relationship of beams 100% pre-loaded. The peak moment capacities were observed between 11.37 to 17.10 kN.m. From Table 4.2 it can be concluded that all beams had good energy dissipation and desirable failure modes.as the ductility ratios were above 2.0. These values meet the requirement relating to ductile failure.

4.2.2 Behavior of beams on 75% Pre - Loading

After 100% loading, CB -7 and CB- 8 were loaded on UTM machine and 75% of average ultimate load taken by CB-1 and CB-2 was applied (i.e., 47.55 KN). In case of CB-7, the initial hair line crack developed at 9.13 KN and later cracks

Table 4.2: Moment Curvature and Ductility Ratios of beams 100% pre-loaded

Beam	**Peak Moment (kNm)**	**Yield Curvature (rad)**	**Ultimate Curvature (rad)**	**Ductility (ϕ_u/ϕ_y)**
CB1	17.10	1.18e-4	2.48e-4	2.10
CB2	16.95	1.20e-4	2.51e-4	2.09
BB3	13.81	1.08e-4	2.17e-4	2.00
BB4	12.10	1.01e-4	2.15e-4	2.12
BU5	13.07	9.80e-5	2.35e-4	2.40
BU6	13.98	9.90e-5	2.13e-4	2.15

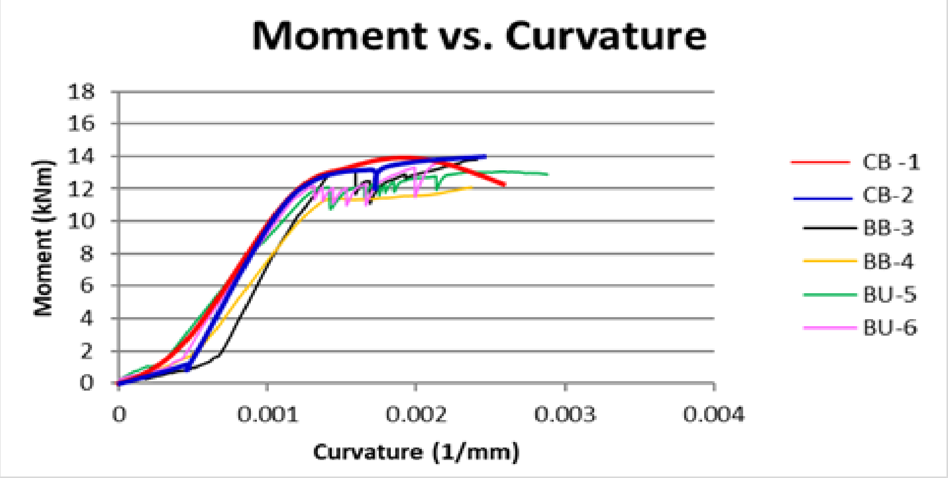


Figure 4.4: Moment vs curvature relation of beams before strengthening (100% pre-loaded)

started travelling from tension to compression zone. The test on CB-7 and CB-8 was stopped after 265 and 271 secs respectively once applied load reached 47.55 KN.

Similarly, BB-9, BB-10, BU-11 and BU-12 were tested up to 47.55 KN (75% load) to generate stresses in beams for later strengthening as discussed earlier. The load deflection curves of beams followed a steep slope (linear relation) and are shown in Figure 4.5. The deflection observed in CB-7 and CB-8 was 4.74 and 4.55 mm respectively.

Table 4.3: Physical Observation and load taken by beams after strengthening

S. No.	**Beam**	**Load on First Crack (KN)**	**Load on Additional Cracks (KN)**			**Ultimate Load (KN)**	**Deflection (mm)**	**Time(S)**
			2nd Crack	**3rd Crack**	**4th Crack**			
1	BB-3	9.64	25.54	50.68	61.5	66.73	18.13	401
2	BB-4	10.66	17.64	37.1	43	54.02	18.2	386
3	BU-5	15.54	27.2	49.4	68.45	73.66	15.913	418
4	BU-6	12.54	25.38	41.085	67.89	70.35	18.122	428
5	BB - 9	11.3	19.41	37.56	59.01	66.35	10.598	382
6	BB - 10	10.43	23.63	43.33	62.2	78.48	9.812	409
7	BU - 11	13.83	41.01	79.77	94.3	101.63	9.559	434
8	BU -12	9.44	15.58	39.9	48.9	52.66	8.305	204

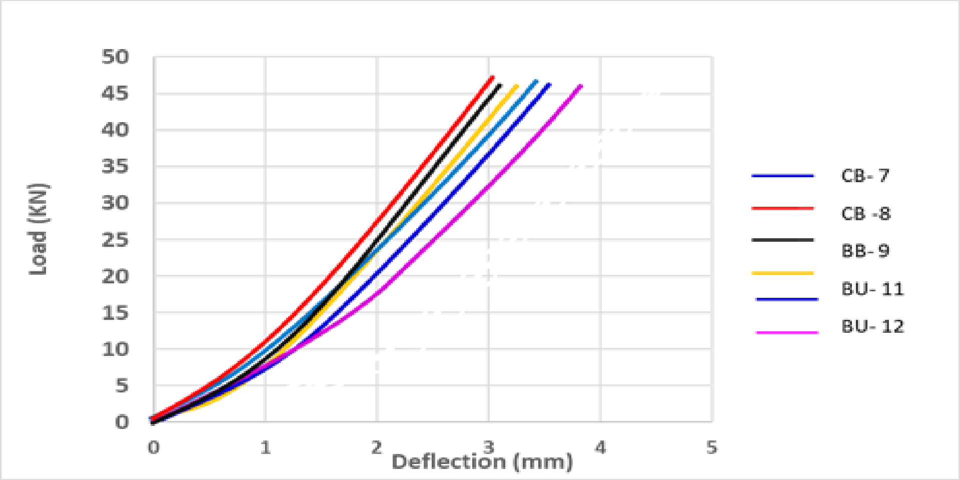


Figure 4.5: Load Deflection Curves of beams before strengthening on 75% loading

4.3 Behavior of Loaded Beams After Strengthening

After initial load testing of beam specimens, strengthening of beams as mentioned in Table 3.4 was carried out as per scheme elaborated in para 3.3.2. The Table 4.3 shows the observation such as initial crack loads, yielding load, ultimate load, and deflection. It is highlighted that crack developed in beams during initial test were not repaired or injected with epoxy filling however, only primer was applied on sides of beam which were reinforced in U shape. The beams were tested under four-point loading at constant rate of 1mm / min. During loading each beam showed unique behavior, crack pattern and failure mode.

4.3.1 Behavior of Beams after strengthening (100% preloaded)

From test data and physical observation, it is deduced that ultimate strength of BB-3, BB-4, BU-5 and BU -6 not only regained their initial ultimate strength, but it increased by 9% ,1% 26% and 13% respectively. During the test process of BB-3, it was observed that initial narrow micro cracks were developed in the UHPC layer at 9.64 KN and later the cracks started to develop in the already stressed concrete portion as shown in Figure 4.6 (a). The cracks in concrete kept widening as load was progressively applied to test the ultimate strength of the beam. It was observed during testing that CRFP laminate didnt split or crack and very minimal debonding of CFRP occurred especially near supports. The ultimate load taken by BB-3 was 66.73 KN which is 9% greater than initial test strength. After testing of BB-3, BB-4 was tested as shown in Figure 4.6(b). The test results of BB-4 showed a similar behavior as of BB-3 except that it took ultimate load of 54.02 KN which is 1% greater than initial load taken before strengthening.

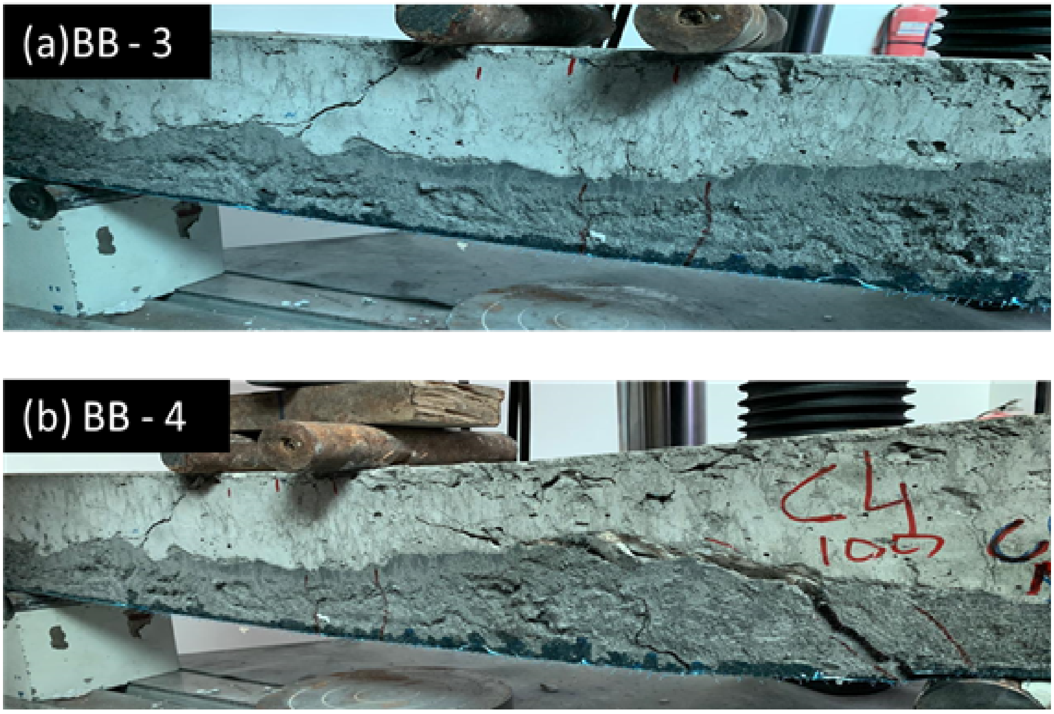


FIGURE 4.6: Behaviour of BB-3 and BB-4 during test after strengthening

Later, BU-5 and BU-6 reinforced with UHPC and U shape CRFP were tested for ultimate loading. Both the beams had significant increase in their ultimate strength despite initially tested on 100% loading. The increase in ultimate strength of BU-5 and BU-6 was 26% and 13% respectively. The crack pattern and behavior of CRFP was similar to BB-3 and BB-4. In case of BU -6, no splitting of CFRP was seen however, clear deflection was observed as shown in Figure 4.7. It was very clearly seen that fibers in UHPC layer got stretched but were not broken as shown in Figure 4.8. The stretching of fibers and narrow cracks in UHPC indicate that fibers performed their intended purpose. Once compared with CB 1 & 2, the average increase in ultimate strength of BB-3 and BB-4 was -5% and in case of BU-5 and BU-6 the average increase in ultimate strength was 14% after regaining initially tested strength.

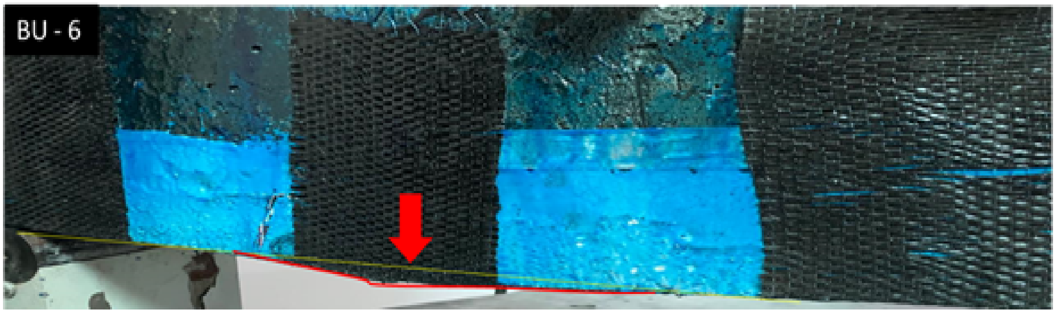


Figure 4.7: No splitting of CFRP and bending observed in BU-6

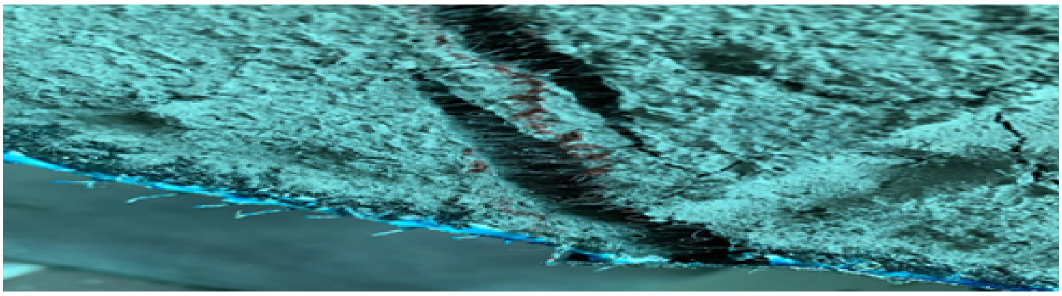


Figure 4.8: Stretching of fibers in UHPC section

4.3.1.1 Load Deflection Relationship

The load deflections curves of beams after strengthening (100% pre-loaded) are shown in Figure 4.9. For all beams except BB 4, it can be clearly seen that the curve up to yield point followed a linear pattern which is desirable and shows increased stiffness. After that the beams made a soft peak followed by progressive drop in load as the cracks started to widen. In case of BB-4, the slope did not follow a linear relation indicating decline in stiffness. This can be attributed to poor strengthening of beam. In case of BB-3, the beam had a dip after yield point but regained its strength and started load again and performed 13% higher than load tested initially. This sharp dip is attributed to machine adjustment or crack widening.

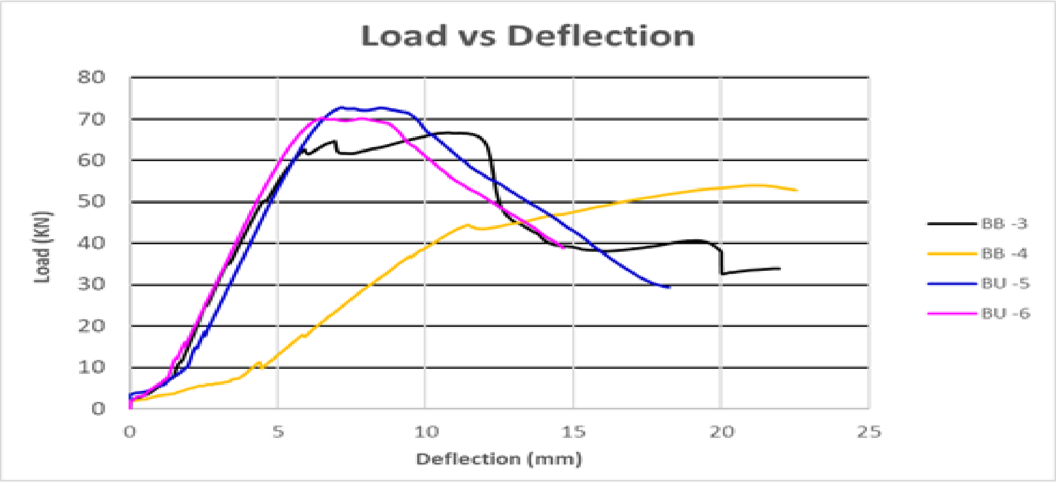


FIGURE 4.9: Load deflection curves of beams after strengthening (100% pre-loaded)

4.3.1.2 Moment Curvature Relationship

Using the classic equation 3.1 and 3.2, moment and curvature were calculated and tabulated in Table 4.2 whereas, Figure 4.10 graphically represents the moment curvature relationship of beams after strengthening which were 100% pre-loaded.

The peak moment capacities were observed between 12.15. to 16.375 kN.m. Based on the momentcurvature analysis, all beams demonstrated ductile behavior, meeting ACI 318 requirements for ductile failure modes in flexural members.

TABLE 4.4: Moment Curvature and Ductility Ratios of beams 100% pre-loaded

Beam	**Peak Moment (kNm)**	**Yield Moment (kNm)**	**Yield Curvature (rad)**	**Ultimate Curvature (rad)**	**Ductility (ϕ_u/ϕ_y)**
BB-3	15.014	11.261	0.00003957	0.000155	3.91
BB-4	12.155	9.117	0.00003116	0.000102	3.29
BU-5	16.375	12.28125	0.00003557	0.000118	3.33
BU-6	15.831	11.875	0.00003357	0.000119	3.56

All beams sustained deformations well beyond yielding before failure. The yield curvatures observed were low, reflecting timely yielding, while the ultimate curvatures confirmed good post-yield deformation capacity. Overall, all beams not only achieved satisfactory strength but also exhibited ductility, showing that strengthening scheme performed its intended purpose.

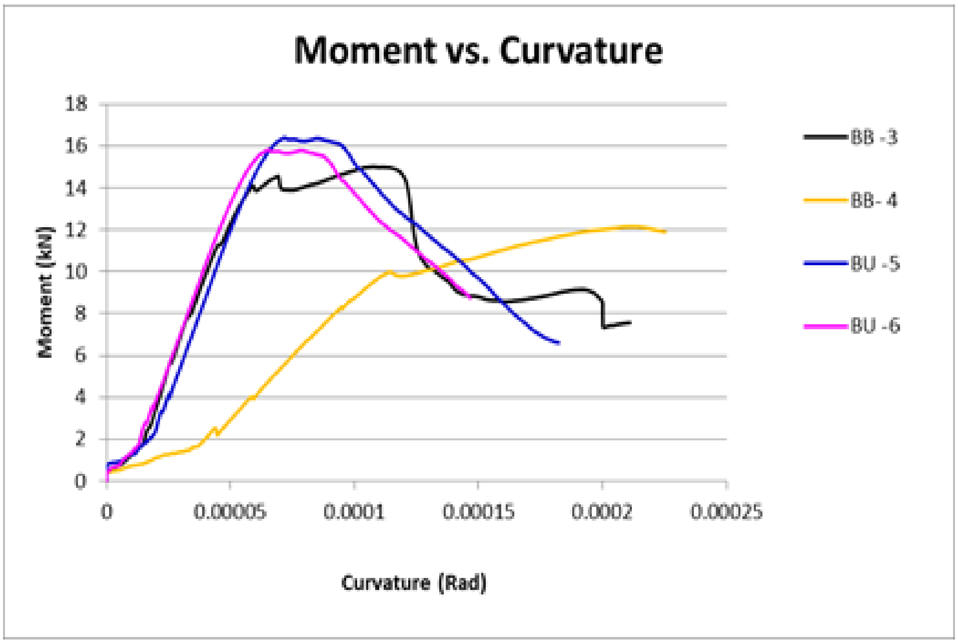


FIGURE 4.10: Moment vs curvature relation of beams after strengthening (100% pre-loaded)

4.3.1.3 Comparison of Load Deflection Curves of unstrengthen and strengthened beams (100% pre-loaded)

In Figure 4.11 (a), comparison of load deflection curves (before and after strengthening) of BB-3 and BB-4 has been shown. It is clearly visible that for BB-3, the slope was much steeper and did not follow the same pattern after yield point as observed in initial test. This clearly shows increased stiffness of beam after strengthening with UHPC and CFRP on soffit. In case of BB-4 it was identical before after strengthening with UHPC and CFRP. In case of BU-5 and BU-6, the curves were much steeper after strengthening up to yield point which later flattened and later got dipped as shown in Figure 4.11(b). From comparison of curves of BU-5 and BU -6, it can be concluded that stiffness of beam had increased much higher with UHPC and CFRP in U shape pattern.

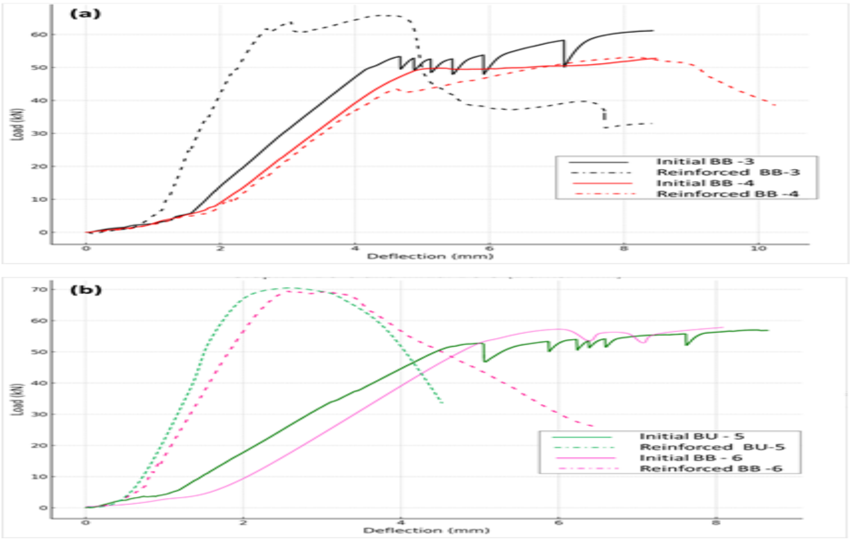


FIGURE 4.11: Comparison of load deflection curves (a)BB-3 & BB-4 (b) BU-5 & BU6

4.3.2 Behavior of Beams after strengthening (75% pre-loaded)

In case of 75% pre-loaded beams, after strengthening, BB-9 and BB-10, regained additional strength by 40% and 65% respectively. The average increase in strength after reinforcement with UHPC and CRFP along bottom surface is 52% which is greater than average of ultimate strength of CB-1 and CB-2 by 14%. The crack pattern near the supports was observed and behavior of UHPC and CRFP was similar to earlier beams as shown in Figure 4.12(a). In case of beam specimen BU-11, it showed 114% increase in strength after initially regaining the 75% strength. The cracks in BU-11 were visible between the gaps of CFRP fixed in U shape as shown in Figure 4.12(b). In case of BU-12, it could only achieve 11% more strength than 75% load test and 16% less than average of CB-1 and CB-2. This poor result of BU-12 can be attributed to improper strengthening in U shape CRFP. The overall crack pattern was similar having initial micro cracks in UHPC and later in concrete portion.

4.3.2.1 Load Deflection Relationship

The load deflections curves of beams after strengthening (75% pre-loaded) are shown in Figure 4.13. The behavior of the tested reinforced concrete beams,

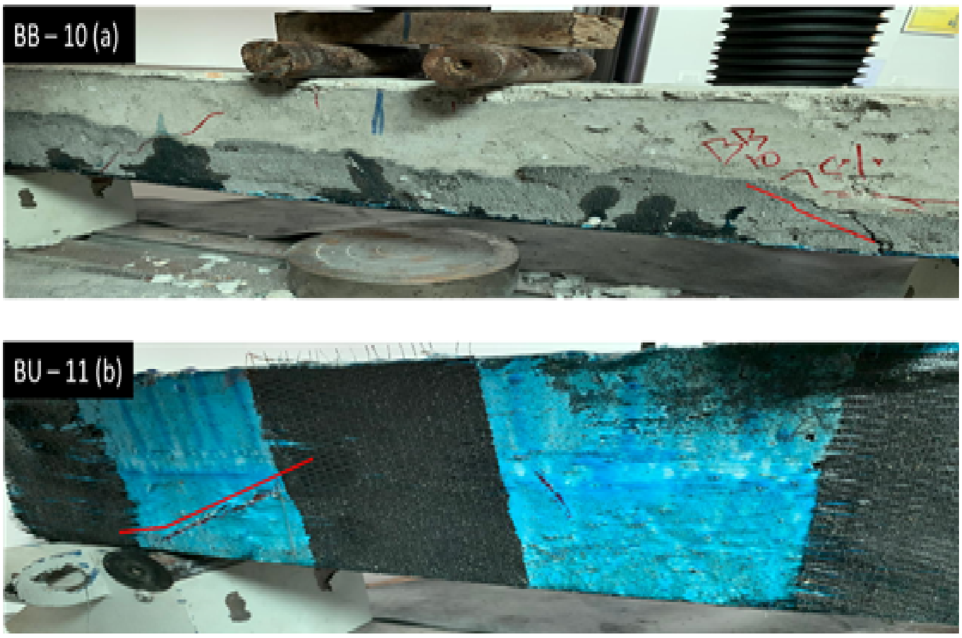


FIGURE 4.12: Behaviour of beams during test after strengthening (75% preloaded)

evaluated through both load-deflection relationship, gives significant insights into their structural performance. The initial stiffness is evident from the slope of the linear portion of the load-deflection curves. BB- 9 and BU-11 which achieved peak loads of 78.49 kN and 101.63 kN, respectively, formed steeper initial slopes, indicating higher elastic stiffness and a delayed onset of cracking. On the other hand, BU-12, with a peak load of 52.68 kN, exhibited a smaller slope, suggesting lower initial rigidity and potentially earlier cracking due to poor strengthening of beam with UHPC and U shape wrap.

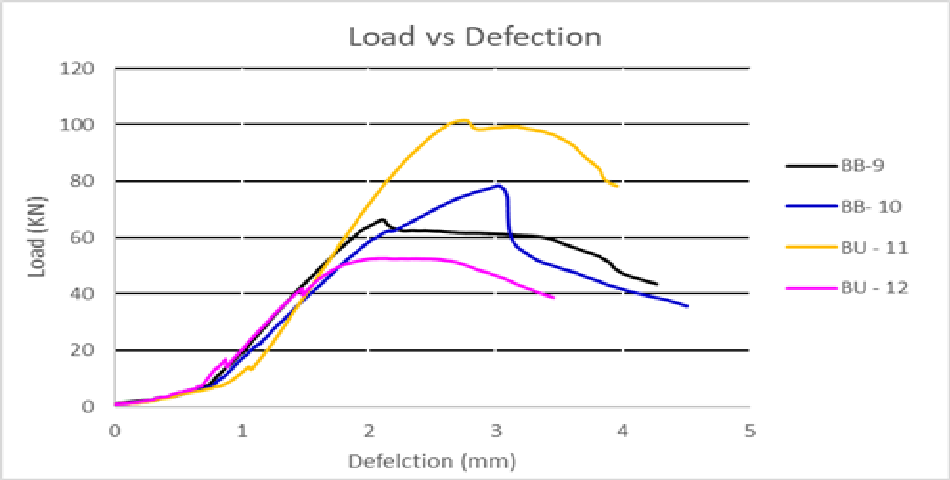


FIGURE 4.13: Load deflection curve of beams after strengthening (75% preloaded)

4.3.2.2 Moment Curvature Relationship

Using the classic equation 1 and 2, moment and curvature were calculated and tabulated in Table 4.5 whereas, Figure 4.14 graphically represents the moment curvature relationship of beams after strengthening which were 75% pre-loaded. From a strength perspective, BU -11 a recorded the highest peak moment of 22.87 KNm, followed by BB 9 at 17.66 KN.m, reflecting their superior load-carrying capacities. Moment-curvature analysis further supports these observations as these beams exhibited greater curvatures ductility. Besides, aall beams showed ductility ratios > 2 except BU -12 , indicating effective post-yield deformation, fulfilling requirement of ductile behaviour criteria.

TABLE 4.5: Moment Curvature and Ductility Ratios after strengthening (75% pre-loaded)

Beam	**Peak Moment (kNm)**	**Yield Moment (kNm)**	**Yield Curvature (rad)**	**Ultimate Curvature (1/mm)**	**Ductility (rad)**
BB-9	14.93	11.2	0.00002968	0.00007849	2.64
BB-10	17.66	13.24	0.00003671	0.00009569	2.61
BU-11	22.87	17.15	0.00002566	0.0000634	2.47
BU-12	11.85	8.89	0.00003791	0.00007268	1.92

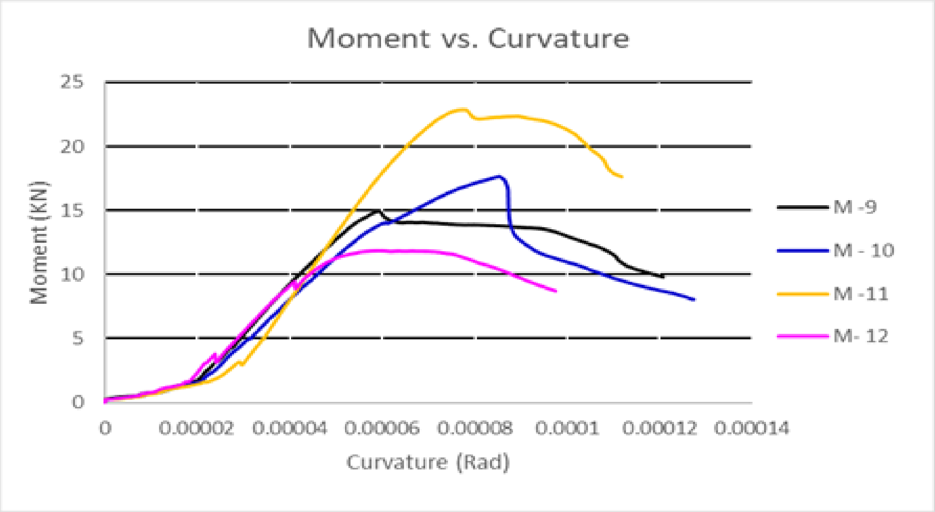


FIGURE 4.14: Moment vs curvature relation of beams after strengthening (75% pre-loaded)

4.3.3 Comparison of Strengthened beams with Control Beams (CB 1 & 2)

The comparison between ultimate strengths of strengthened beams has been compared with control beam CB 1 & 2 and graphically represented in Figure 4.15. It can be observed that average load was much higher than control beams except for average of BB-3 and BB-4 indicating that U shape combination performed better for both 100% and 75% preload beams. The comparison between ultimate strengths before and after strengthening of individual beams has also been tabulated in Table 4. 6. This has been graphically represented in Figure 4.16 as well, showing clear increase in ultimate strength after reinforcement.

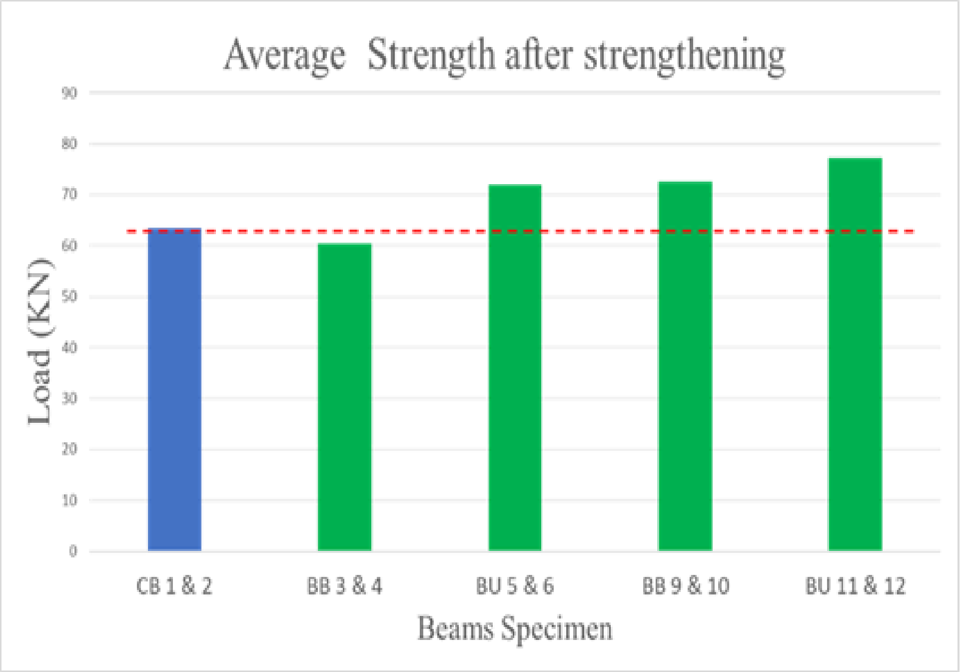


FIGURE 4.15: Comparison of average ultimate strength of beams with control beam CB-1& 2

4.4 Summary

Overall, it can be concluded that development of initial narrow and micro cracks in UHPC and later in concrete indicates that both UHPC and concrete worked together enabling a composite action. It was very clearly seen that fibers in UHPC layer got stretched and were not broken. The stretching of fibers and narrow

Table 4.6: Comparison of Ultimate Strengths before & after Strengthening of each sample beam

S. No.	**Beam Specimen**	**Ultimate Load of beam (KN) before strengthening**	**Ultimate Load by beam (KN) after strengthening**	**Difference after strengthening**
1	BB 3	61.36	66.73	+9%
2	BB 4	53.75	54.02	+1%
3	BU 5	58.04	73.66	+26%
4	BU 6	62.12	70.35	+13%
5	BB 9	47.55 (75% of average of CB 1 & 2)	66.35	+40%
6	BB 10		78.48	+65%
7	BU 11		101.63	+113%
8	BU 12		52.66	+11%

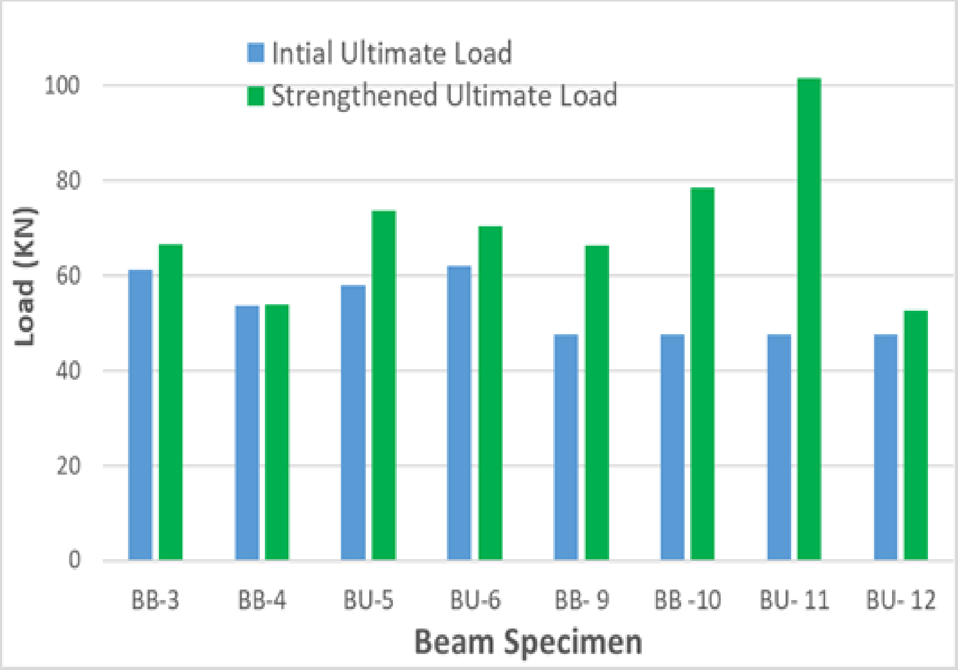


Figure 4.16: Comparison of load taken by beams before and after strengthening

cracks in UHPC indicate that fibers performed their intended purpose and caused a cohesive failure phenomenon. The CRFP had neither cracked nor got split which enabled the beams to take more load, increased stiffness but more bending was observed. Overall, the ultimate load taken by beams increased significantly after strengthening with U wrap system giving higher values as compared to soffit strengthening.

Chapter 5

Conclusions and Recommendations

A hybrid strengthening system comprised of cementitious matrix based ultra-high-performance concrete (UHPC) and carbon fiber reinforced polymers (CFRP), was investigated to strengthen damaged RC beams. Beams were tested up to ultimate loading and 76% loading to simulate the real time conditions. Following are major conclusions from this study:

- It was observed that the hybrid strengthening system of UHPC and CFRP enabled the beams to regain the lost strength up to or even above the strength of the unloaded sound beam. The beams that had not lost all their strength and integrity (i.e., **75% pre-load**) showed much higher ultimate strength compared to the beams which were completely damaged (i.e., **100% pre-load**). The increase in strength is summarized as follows:
  - **30mm UHPC and CFRP at bottom**: The beams pre-loaded up to 100% of their capacity and then strengthened showed an average increase in strength of **5%**, whereas 75% pre-loaded beams showed an average increase of **53%**.
  - **30mm UHPC and U-wrap CFRP**: The beams pre-loaded up to 100% of their capacity and then strengthened showed an average increase in

strength of **19%**, whereas 75% pre-loaded beams showed an average increase of **62%**.

- The load-deflection and moment-curvature relationships showed that UHPC and normal concrete, with the help of fibers, had a composite action which enabled cohesive failure. Furthermore, premature failure or debonding was not observed due to the good bond between the CFRP and UHPC layer. Therefore, the beams after strengthening performed better and showed increased ductility.
- The average increase in strength gained from the combination of 30mm UHPC and U-wrap CFRP shows that this technique performed better than soffit strengthening only.

For future recommendations, it is suggested that:

- Engineered cementitious composites (ECC) alongside fiber reinforced polymers (FRPs) should be considered.
- UHPC and ECC alongside other FRPs such as aramid FRP (AFRP), glass FRPs (GFRP) and basalt FPR(BFRP) should be used to study the sustainability and cost effectiveness of strengthening systems.

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