FLEXURAL PERFORMANCE OF REINFORCED CONCRETE BEAMS
EXTERNALLY STRENGTHENED WITH CARBON
AND BASALT FRP SHEETS

by

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A Thesis Presented to the Faculty of the
American University of Sharjah
College of Engineering
in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Civil Engineering

Sharjah, United Arab Emirates
May 2015
Approval Signatures

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Thesis Title: Flexural Performance of Reinforced Concrete Beams Externally Strengthened with Carbon and Basalt FRP Sheets

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Acknowledgments

I wish to acknowledge the help of my advisor Dr. Rami Hawileh and co-advisor Dr. Jamal Abdalla. They are great mentors who provided me with constant guidance, support, and encouragement.

I wish to thank Mr. Arshi and my colleagues Adi Abdulla and Waleed Nawaz for their assistance in conducting the experimental testing in this research. I would also like to thank my colleague Muḥammad Naser for his help and advice in the numerical simulation included in this research.

I really appreciate all the support and encouragement from my colleagues Ghanīm Kashwani, Lena Alṣamerrai, Haifa Ismāil and Alāʾ Abū Salah, Raʾd Abū Kwaik, and Eḥab Karam.
Dedication

For my family, the greatest source of support and encouragement
Abstract

Different strengthening systems have been widely used for many years to retrofit and repair deficient structural members. Reinforced concrete (RC) slabs and beams are commonly strengthened in flexure by externally bonding Carbon Fiber Reinforced Polymer (CFRP) sheets to the bottom side of the member. The CFRP sheets used in strengthening applications have high strength; however, they are brittle materials with low ductility. Basalt Fiber Reinforced Polymer (BFRP) sheets on the other hand have relatively lower strength compared to CFRP, however they have higher ductility. As a result, there is growing interest among researchers and practitioners in combining different types of FRP sheets to produce an enhanced strengthening system in terms of strength and ductility. This study investigates the flexural behavior of RC beams externally strengthened with CFRP sheets, BFRP sheets, and their hybrid combination (CFRP-BFRP). This hybrid system is designed to enhance the properties of composites, where it combines the high strength of CFRP and high ductility of BFRP sheets, respectively. To investigate the behavior of the different strengthening systems, an experimental program was conducted on ten RC beams that were tested under four-point bending. The load versus mid-span deflection data were recorded and used to compare the performance of the strengthened specimens. The test results indicated that all strengthened specimens yielded higher flexural capacity and lower ductility values compared to the unstrengthened control beam. The increase in the flexural capacity of the strengthened beams ranged from 23% to 68% of the control beam. Moreover, the beams strengthened with BFRP and hybrid CFRP-BFRP sheets achieved higher ductility compared with the beams strengthened with CFRP sheets. Thus, it was concluded that the use of a hybrid combination of CFRP-BFRP sheets could achieve the desired increase in the flexural capacity of RC beams with an improved ductility compared to that with CFRP sheets only. Finite element (FE) models were also developed and were able to capture the behavior of the tested beams with a good level of accuracy. The predicted flexural capacity along with the associated mid-span deflection differed by 1% to 10% from the experimental values.

Search Terms: flexural strengthening, reinforced concrete, beams, FRP sheets, CFRP, BFRP, hybrid combination, finite element modeling.
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Chapter 1: Introduction

1.1. Background

The strengthening or retrofitting of existing concrete structures is frequently required due to deterioration of structural members, excessive loading associated with the change in use of the structure, design or construction errors, inadequate maintenance and exposure to severe environmental conditions. Several conventional materials and construction techniques have been used to strengthen concrete structures. Strengthening and retrofitting increase the load bearing capacity, increase ductility and repair deterioration damages. Traditional strengthening techniques, such as steel plate bonding, section enlargement, reinforced concrete jacketing and external post-tensioning have proved their adequacy in restoring strength and increasing the ductility of various structural elements in different projects.

The growing interest in strengthening and retrofitting techniques stimulated many researches to seek enhancement of existing techniques and search for new innovative ones. As the research field and practical applications of different strengthening materials expanded, some imperfections and limitations associated with each traditional strengthening method were encountered. Steel plates have low corrosion resistance which requires coating and painting and imposes high maintenance costs. In addition, steel plates have a heavy weight by comparison, which increases the dead load of the strengthened or retrofitted structural element. Section enlargement or reinforced concrete jacketing, where additional concrete and reinforcing steel are placed on an existing structural member, is often unfavorable because it reduces the headroom and therefore reduces the usable living area. Moreover, section enlargement is not the best possible strengthening solution in active environments, such as hospitals and schools, because the enlargement process requires site preparation (shuttering, formwork) and produces a lot of noise. Likewise, external post-tensioning is limited to sections with large depth and has a high cost associated with its installation process and tensioning devices.

Fiber Reinforced Polymer (FRP) sheets use resin as a strong alternative to conventional strengthening materials. “An FRP system is defined as all the fibers and resins used to create the composite laminate, all applicable resins used to bond it to the concrete substrate, and all applied coatings used to protect the constituent
materials.”[1]. FRP sheets are gaining a wide acceptance in the industry as the most widely used externally bonded strengthening material due to numerous advantages; such as a high strength/self-weight ratio, high corrosion resistance, resistance to ultra violet radiation and oxidation, durability, ease of installation, speed of construction and design flexibility. In addition, FRP sheets have thin profiles which make them desirable when aesthetics is a concern or when the access is limited, for example a slab shielded by pipe and conduit.

Carbon fiber and glass fiber are two materials suitable for strengthening concrete structures [1]. Over the past two decades, Carbon Fiber Reinforced Polymer (CFRP) has been increasingly used in strengthening and retrofitting RC structural members. The use of CFRP provides a cost effective solution in strengthening structural elements. The CFRP strengthened section gains double the strength, with a moderate increase in stiffness (about 10%). On the other hand, Glass Fiber Reinforced Polymer (GFRP) provides less stiffness and has lower cost than CFRP, which makes it a better alternative, especially in retrofitting seismic damages. Basalt Fiber Reinforced Polymer (BFRP) was recently introduced as an alternative to GFRP due to its superior properties which are high resistance to temperature and chemicals, high tensile strength, and high corrosion resistance.

CFRP, GFRP, and BFRP composites behave in a linear elastic manner until failure, as shown in Figure 1. Unlike steel, these FRP sheets fail in a brittle manner due to FRP rupture or debonding. Beams strengthened with CFRP sheets illustrate lower ductility and higher strength than those strengthened with GFRP or BFRP sheets. Moreover, CFRP has high strength, a high elastic modulus and relatively small elongation at fracture (1-1.5%). Alternatively, GFRP and BFRP have a lower elastic modulus and larger elongation. In order to efficiently utilize the mechanical properties of each FRP sheet and to insure a gradual failure of the composites, a hybrid FRP system was proposed. In this system, different FRP sheets are used with different strengths and stiffness to produce a hybrid system that fails at different strains during loading [2 - 4].
In light of this, the study proposed herein will examine the performance of RC structural members strengthened with hybrid FRP sheets. Within the framework of investigating the best hybrid (CFRP-BFRP) composite scheme, the need for fast and reliable analysis tools arises. Although experimental tests provide the basic information for FE models such as material properties, the development of reliable FE models can reduce the number of test specimens needed. Recognizing that experimental tests are time-consuming and costly, complex analyses of RC structural members strengthened with hybrid FRP sheets can be carried out in a fast and effective fashion using FE modeling.

1.2. Research significance

Structures all around the world are susceptible to deterioration and damage. Even the most modern structures such as skyscrapers and bridges are susceptible to degradation. Although these mega-structures are designed to have a service life of 60-80 years, they often need regular maintenance and repairs. These structures are required to maintain a certain performance level, which includes load carrying capacity, durability, function and aesthetic appearance.
The dynamic changes that occur in our daily lives change the loading type or impose more loads on existing structures. During the last decades, cities witnessed increased rates of population growth and transportation has become heavier and more frequent. This imposes a greater load bearing capacity demand on bridges. Furthermore, some structures are deficient due to design errors or mistakes during construction. Other structures need upgrading due to temporary overload. To keep these deficient structures in service, they are upgraded, replaced or their use is restricted. These solutions are usually costly and ineffective. Hence strengthening is usually needed for various reasons to keep the structures at a certain performance level.

During the last decade, strengthening concrete structures with advanced FRP composite materials has gained wide acceptance. FRP sheets are bonded to the surface of deteriorated or deficient structural members to increase their load bearing capacity and ductility. CFRP and GFRP are two common composites with high tensile strength and relatively high stiffness, which are used as additional reinforcement to strengthen RC members [6]. FRP composites are elastic materials and their failure is brittle. Experimental investigations have shown that RC members strengthened with FRP sheets experienced a sudden failure due to FRP rupture or FRP debonding. For that, improvements in strength and stiffness of the strengthened member are limited. The use of hybrid FRP composites emerges as an effective solution to integrate strength and ductility of different fibers. In this system, each FRP sheet fails at different strain that produces a gradual failure of the hybrid system, and the strengthening effects of FRP composites are fully utilized. Even when maintaining the same steel reinforcement amount, the hybrid FRP system will improve strength, stiffness and elongation properties. Consequently, RC structural members strengthened with hybrid FRP composites present an enhanced load bearing capacity, stiffness, and durability [7], [8].

In this research, the overall behavior of RC structural members strengthened with hybrid CFRP- BFRP composites was investigated. An experiment was held to test RC beams strengthened with different arrangements of hybrid CFRP-BFRP sheets. Moreover, a general-purpose finite element program, ANSYS, was used to simulate the flexural behavior of RC beams strengthened with a hybrid CFRP-BFRP system. Therefore, the significance of this research is to explore and validate the use
of hybrid CFRP-BFRP sheets as a strengthening composite that embodies the high strength of CFRP sheet and the high ductility of BFRP sheet.

1.3. **Research objectives**

This study aims to investigate the flexural performance of RC beams strengthened with hybrid CFRP- BFRP laminates.

The primary objectives of this research are:

1. Study the effect of combining CFRP and BFRP sheets on the overall strength and ductility of the strengthened beams.
2. Investigate the effect of changing the sequence of CFRP and BFRP layers on the structural behavior and performance of the RC beams by conducting an elaborate experimental program.
3. Develop FE models which simulate the behavior of RC beams strengthened with hybrid CFRP-BFRP systems.
4. Verify the developed FE models by comparing the experimental and simulation results.

1.4. **Thesis organization**

Chapter 1 of this thesis is the introduction of the research, and it includes background of the research, research significance and research objectives. Chapter 2 provides a literature review on different types of FRP sheets used for RC beam strengthening. Chapter 3 explains the experimental program conducted to investigate the behavior of the strengthened beams. It includes a full description of the tested specimens, material used, test setup, and test matrix. Chapter 4 summarizes the experimental results and compares the behavior of different strengthening combinations of CFRP and BFRP sheets. Chapter 5 describes the development of the finite element models that simulated the tested RC beams. It explains the element types and material consecutive models used in this research. Chapter 6 presents the finite element model results. It first starts with the process of finite element model validation against the experimental results; consequently it presents different result outputs that are used to analyze the behavior of FRP strengthened beams. Finally, Chapter 7 presents a summary and conclusion of this research.
2.1. **Carbon fiber reinforced polymer (CFRP)**

CFRP is a very strong and light composite material, which consists of carbon fibers embedded in a thermosetting resin known as the matrix. This high performance material has been widely used due to its various advantages. It has a very high modulus of elasticity, high tensile strength (may reach 1000 ksi / 7 GPa), low density (114 pcf /1800 kg/m³), good corrosion resistance, low coefficient of thermal expansion, and high chemical inertness. Yet, CFRP sheets are relatively expensive, have high electric conductivity, and fail in a brittle manner.

CFRP has been increasingly used in various fields such as aerospace engineering (Airbus A350 wings), manufacturing automotive parts, sports goods (tennis racquets and bicycle frames subjected to high stresses), pumps and drive shafts, and many other industrial applications. However, using CFRP composites in structural engineering applications started in the 1980’s. Since then, CFRP has been effectively used to strengthen concrete, masonry, steel, and timber structures. Besides using CFRP for retrofitting or strengthening deteriorated structural members, it has been efficiently used as an alternative to steel reinforcement. Many studies concerned with the flexural strengthening of RC reported that CFRP significantly increases the strength but only slightly improves the ductility of those structural members.

Ashour et al. [9] tested 16 beams to study the “flexural strengthening of RC continuous beams using CFRP laminates”. They concluded that CFRP strengthened beams demonstrated higher load capacity but lower ductility than unstrengthened beams. Moreover, they indicated that strengthened beams failed dominantly in a brittle manner, where the concrete cover adjacent to the CFRP sheets peeled suddenly.

Ahmad et al. [10] conducted an experimental investigation to evaluate the flexural performance of RC beams strengthened with CFRP sheets with different arrangement schemes. They reported that CFRP strengthening has greatly improved the load carrying capacity of reinforced concrete beams. Moreover, they revealed that increasing the number of CFRP laminate layers increases the flexural stiffness, yield load, and ultimate load. In addition, they observed that no inter-layer delamination occurred; rather the strengthened beams failed suddenly in a brittle manner.
Dong et al. [11] studied the flexural behavior of strengthened RC beams. They tested seven beams with different cross section depths, longitudinal reinforcement, and concrete cover thickness. They concluded that retrofitting reinforced concrete beams with CFRP sheets increased the strength by 41-125%. Besides, they stated that the stiffness did not change by increasing the concrete cover thickness.

Haritos et al. [12] presented the results of retrofitting two 40% scale flat slab models, which were significantly damaged from static testing. They concluded that CFRP was a useful material for strengthening RC members with severe damages caused by static overload or extreme earthquakes.

Esfahani et al. [13] tested 12 RC beams with three different reinforcement ratios. The authors used CFRP sheets with different widths, lengths, and number of layers to strengthen RC beams and study their behavior. It was concluded that the flexural strength and stiffness of the strengthened beams were higher than un-strengthened beams. Moreover, the authors found that when small reinforcement ratios were used, the flexural strength of beams calculated using the design guidelines in ACI 440.2R-02 and ISIS Canada were overestimated. Hence, they recommended using the two guidelines for high reinforcement ratios.

Soudki et al. [14] studied the behavior of CFRP strengthened beams subjected to a corrosive environment. They concluded that strengthened beams produced double the strength of un-strengthened beams even when subjected to harsh environment.

Aboutaha et al. [15] studied the flexural ductility of RC beams strengthened with CFRP sheets. They experimentally investigated nine RC beams strengthened with CFRP sheets. The authors concluded that the flexural ductility of the beams improved by increasing the steel reinforcement. In addition, providing anchors in the strengthening system prevented delamination of the CFRP sheets which increased the flexural ductility of the strengthened RC beams.

There are many other experimental studies, [16]-[18], that investigated the flexural behavior of RC beams strengthened with CFRP laminates. They all indicated that failure modes, including CFRP delamination, limited the strengthening effect.
2.2. Glass fiber reinforced polymer (GFRP)

GFRP consists of a polymer matrix reinforced with fine glass fibers. The constituents of GFRP are abundant materials, readily available and inexpensive, which makes it cheaper than CFRP. Ehsani [19] reported that the pure cost of CFRP sheets is two to three times higher than that of GFRP sheets, depending on the thickness or strength of the sheets. In addition, GFRP has many superior properties such as high stiffness to weight ratio, high modulus of elasticity, high resistance to corrosion and chemical attack, and good insulating properties [20]. On the other hand, GFRP has low thermal and acid resistance, low interfacial properties, and lower strength properties than CFRP.

GFRP has been a favorable material in many industries such as manufacturing boats and marine structures, automobile panels, aircraft wings, pressure vessels, pipes, and many other applications. Moreover, many studies have investigated the use of GFRP sheets in structural applications.

Saadatmanesh et al. [21] conducted an experimental study to examine RC beams strengthened with GRFP plates. They reported that bonding GFRP plates to the tension face of RC beams significantly increased the flexural strength. Furthermore, an improved cracking behavior was reported, where smaller crack widths were obtained at higher loads.

A field application of GFRP was demonstrated by Ehsani et al. [22], where the GFRP strengthening technique was used to retrofit an industrial complex severely damaged during the Northridge earthquake of January 17, 1994. Bonding GFRP to RC walls was proved to enhance the structural behavior and to be an economical solution.

Leung [23] studied the flexural and shear behavior of RC beams externally strengthened with GFRP plates. The experimental results indicated that GFRP strengthening enhanced the strength and the ductility capacities of RC beams. Moreover, the author stated that a reduced deflection is achieved when GFRP plates are bonded simultaneously on the bottom and on the sides of deficient RC beams.

2.3. Basalt fiber reinforced polymer (BFRP)

BFRP was originally developed in the United Soviet with strict secrecy and was used in aeronautic and space industries. Since then BFRP has been increasingly
used in many applications for its numerous advantages such as resistance to high
temperature, durability, and resistance to chemicals and alkaline. Besides, BFRP has
several advanced properties making it a very favorable material in structural
applications. BFRP has a similar coefficient of thermal expansion as concrete, natural
resistance to corrosion, alkali, and acids, and does not absorb or transfer moisture like
GFRP. Furthermore, BFRP laminates are remarkable in terms of fire resistance,
which make them emerge as a strong alternative to other types of FRP composites.

Sim et al. [24] performed a comprehensive study to investigate the durability,
mechanical properties, and strengthening effect of BFRP sheets. The authors studied
the performance of different types of FRP composites under severe environmental
conditions. They concluded that BFRP exhibited a lower strength reduction rate than
GFRP when exposed to accelerated weathering conditions. Besides, BFRP showed
superior performance when exposed to high temperature (600 °C), where 90% of its
strength was maintained. Also, the authors conducted flexural tests on RC beams
strengthened with BFRP sheets. They concluded that using two layers of BFRP was
the best strengthening scheme to increase the flexural capacity of RC beams. It was
also noted that the structural strengthening effect of CFRP and GFRP were higher
than BFRP; however, when moderate strengthening and high resistance to fire are
required, BFRP arises as a strong alternative among other FRP strengthening systems.

Serbescu at al. [25] investigated the applicability of using BFRP to strengthen
RC beams. They verified that using BFRP as external reinforcement provides a cost
effective, durable solution when moderate strengthening and high heat resistance are
required.

Lopresto et al. [26] performed several experimental tests to compare the
mechanical properties of BFRP and E-glass FRP laminates. Although the results
showed that E-glass FRP laminates were superior in terms of tensile strength, BFRP
laminates exhibited 35-42% higher elastic modulus, better flexural behavior, and
higher impact force and energy than E-glass FRP laminates.

2.4. Hybrid FRP Systems
Xiong et al. [27] examined the behavior of RC beams strengthened with
hybrid carbon fiber-glass fiber sheets. The authors tested six beams strengthened with
either a hybrid FRP system or CFRP only. They concluded that using the hybrid FRP
system increased the deflection ductility by 89.7% and reduced the stiffness and strengthening cost by 10% and 38% respectively, when compared with using CFRP sheets only.

Kim et al. [28] studied the structural behavior of RC beams retrofitted with hybrid FRP systems. They investigated the effect of using different sequences of CFRP and GRPF sheets. Moreover, they examined beams preloaded up to 50% and 70% of the ultimate strength. Consequently, they studied the effect of preloading on the flexural behavior of the strengthened beams. The authors used several FRP sheet combinations, which included two and three layers of FRP laminates. They concluded that using a hybrid FRP system is more effective in strengthening beams than using a single layer of FRP. Besides, applying GFRP prior to CFRP provided higher strength and ductility than applying CFRP first. Furthermore, they concluded that using a GCC (Glass-Carbon-Carbon) combination is the most effective strengthening system. This combination yielded the largest maximum load and the smallest mid-span deflection. The authors also stated that a hybrid FRP system is less effective when applied to a preloaded beam, because the preloading develops cracks in the beam which prevent full transfer of the load to FRP sheets.

Grace et al. [29] developed an innovative pseudo-ductile FRP strengthening fabric. The hybrid fabric includes three types of fibers, namely: ultra-high modules carbon fibers, high modulus carbon fibers and E-glass fibers. This fabric was designed to have the potential to yield simultaneously with the steel reinforcement. The authors tested thirteen RC beams with different strengthening systems. They strengthened the beams with carbon fiber sheets, carbon fiber plates, carbon fiber fabrics and hybrid FRP fabrics. After testing the beams under four point bending, the authors concluded that a higher increase in yield load is obtained when a hybrid FRP fabric is used than when carbon fiber system is used.

Hosny et al. [30] studied the performance of RC beams strengthened by hybrid FRP laminates. They tested seven beams in four-point bending under cyclic loading and performed an analytical study. The authors varied the percentage of steel reinforcement, type of hybrid FRP, location of FRP and ratio between CFRP and GFRP. They concluded that strengthening RC beams with CFRP or GFRP laminates increases the ultimate load carrying capacity; however, the ductility is significantly
reduced. On the other hand, using hybrid FRP laminates enhanced the ductility of strengthened beams.

Li-juan et al. [31] used finite element modeling (FEM) to investigate the interfacial stress of RC beams strengthened with a hybrid FRP system. The authors indicated that performing this analysis would help in developing a safe and economic design of hybrid FRP systems. The FEM presents a detailed distribution of normal and shear stresses along the interface. It was observed that these stresses increase nonlinearly at first, and then diminish with the distance away from the FRP end. Moreover, the authors concluded that debonding failure initiation is delayed when a hybrid FRP system is used.

Wu et al. [32] proposed a novel hybrid FRP-concrete structural system. The tensile load is carried by CFRP sheets bonded to the bottom surface of concrete. The shear loads are resisted by GFRP sheets wrapped in hoops around the concrete beams. Six beams were tested under four-point bending tests. The authors concluded that using hybrid FRP composites increased load carrying capacity, ductility and stiffness. Moreover, a better crack distribution behavior was observed when minimum reinforcing rebars were provided. In addition, the authors suggested that bonding hoops of GFRP sheets helped in preventing premature debonding of longitudinal CFRP, hence increasing the load carrying capacity of the hybrid system significantly.

Choi et al. [33] studied the flexural and bond behavior of concrete beams strengthened with hybrid carbon-glass FRP sheets. They studied the effect of changing the ratio of glass to carbon fibers and they concluded that a ratio of 6.8 to 1 or higher promoted a pseudo-ductile behavior. When a glass to carbon ratio of 6.8/1 was used, the peak load increased by 20% compared to un-strengthened beam.

Hawileh et al. [34] studied the flexural behavior of RC beams externally strengthened with hybrid CFRP-GFRP sheets. The authors tested five RC beams under four point bending. The tested beams included one un-strengthened beam, one beam strengthened with a CFRP sheet, one beam strengthened with a GFRP sheet, one beam strengthened with CFRP and GFRP sheets, and one beam strengthened with two layers of GFRP sheet and one layer of CFRP sheet. The authors concluded that the increase in the load carrying capacity of the strengthened beams ranged from 30% to 98%. Moreover, they observed that RC beams strengthened with GFRP sheets and
hybrid combinations of CFRP- GFRP sheets provided higher ductility than beams strengthened with CFRP sheet only. Finally, the authors recommended the use of hybrid CFRP- GFRP system for external strengthening of RC beams.

It is clear that hybrid CFRP-GFRP strengthening systems have been used extensively and are proven effective in increasing both strength and ductility. However, the hybrid CFRP- BFRP strengthening system was not studied. Therefore, the importance of this investigation becomes evident to contribute to this missing body of knowledge.
Chapter 3: Experimental Program

This experimental program was conducted to investigate the flexural behavior of RC beams externally strengthened with different combinations of CFRP-BFRP sheets. In this program, the number of FRP sheets used for strengthening was varied and the sequence of CFRP and BFRP layers was interchanged.

3.1. Test specimens

A total of ten RC beams with an average concrete compressive strength of 38.78 MPa were tested. Nine beams were strengthened with different combinations of CFRP and BFRP sheets, and one beam was used as an unstrengthened control specimen. All beams were 120mm x 240mm in cross-section and 1840 mm in length. The tension reinforcement included two deformed steel rebars with 10 mm diameter, located at an effective depth of 202mm. Two deformed steel rebars with 8 mm diameter were placed at a depth of 37 mm, to serve as compression reinforcement. A clear concrete cover of 25mm was maintained around the cross-section of the beam. To prevent shear failure, stirrups with 8 mm diameter were used and spaced at 80 mm center-to-center. The FRP laminates were attached externally to the beam’s tension face via epoxy adhesive. All beams were tested under four point bending. Figure 2 shows the specimen dimensions and details.

![Figure 2: Specimen dimensions and details (mm)](image-url)
3.2. Materials

3.2.1. Concrete

Concrete cylinders were casted and tested for compressive strength after 28 days. A compression test machine was used to test three concrete cylinders having a length of 300mm and diameter of 150mm. Figure 3 shows a concrete cylinder sample mounted in the compression test machine. Figure 4 shows a sample of the tested (crushed) cylinder. The average compressive strengths are listed in Table 1.

![Figure 3: Concrete compressive strength test set-up](image)

![Figure 4: Concrete cylinders - compressive strength test](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cylinder 1</th>
<th>Cylinder 2</th>
<th>Cylinder 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength (KN/m²)</td>
<td>35.82</td>
<td>37.17</td>
<td>43.34</td>
<td>38.78</td>
</tr>
</tbody>
</table>

Table 1: Concrete compressive strength calculations

3.2.2. Steel rebar

A uniaxial tensile test was conducted to measure the tensile mechanical properties of steel rebars. Figure 5 shows a steel rebar during the tensile test. Stress-strain curves of steel rebars were obtained from the test as shown in Figure 6. The average values of yield strength, tensile strength, and elastic modulus were 540 MPa, 640 MPa, and 200 GPa, respectively. The tensile test results are summarized in Table 2.
Figure 5: Steel rebar tensile test

![Steel rebar tensile test](image)

Figure 6: Stress-strain curve of tested steel rebars

![Stress-strain curve](image)

Table 2: Coupon test results of steel

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Rebar 1</th>
<th>Rebar 2</th>
<th>Rebar 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (MPa)</td>
<td>544.35</td>
<td>538.78</td>
<td>537.28</td>
<td>540.14</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>633.20</td>
<td>655.05</td>
<td>632.26</td>
<td>640.17</td>
</tr>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>199.91</td>
<td>200.02</td>
<td>199.99</td>
<td>199.97</td>
</tr>
</tbody>
</table>
3.2.3. Epoxy

Sikadur-330, a 2-part epoxy resin, was used to attach FRP sheets to the tension face of concrete beams. The epoxy is manufactured for manual mixing and application. The service temperature for this epoxy is between -40°C to +50°C. The manufacturer provides the mechanical properties of the epoxy resin after 7 days at 23°C. The manufacturer specifies a tensile strength, flexural elastic modulus, and tensile elastic modulus of 30 MPa, 3800 MPa, and 4500 MPa, respectively [35]. Figures 7 and 8 show the epoxy resin used in this study.

![Figure 7: Sikadure-330 - Epoxy resin](image1)
![Figure 8: Sikadure-330 – Mixed Epoxy resin](image2)

3.2.4. FRP sheets

CFRP and BFRP sheets were used for strengthening the RC beams. They were attached to the tension face of the concrete beam via epoxy adhesive. To study the strengthening effect of the hybrid system, the beams were strengthened with different combinations of CFRP and BFRP sheets.

3.2.4.1 CFRP

The CFRP used in this project was SikaWrap-300 C/60, a unidirectional woven carbon fiber used for dry or wet application processes, as shown in Figure 9. It can be used for flexural and shear strengthening of concrete structures, brickwork, and timber. SikaWrap-300 C/60 is a lightweight material with a total areal weight of 300 g/m² ± 15 g/m², which contains black carbon fibers (99% of total areal weight) woven by white thermoplastic heat-set fibers (1% of total areal weight). The manufacturer
specifies a fiber design thickness of 0.166 mm. The manufacturer also provides the dry fiber properties, which include tensile strength, tensile elastic modulus, and elongation at break which equals 3900 N/mm\(^2\), 230000 N/mm\(^2\), and 1.5\%, respectively [36].

![Figure 9: CFRP sheet](image)

### 3.2.4.2 BFRP

The BFRP used to strengthen the RC beams was FIDBASALT UNIDIR 400 C95, provided by FIDIA Technical Services, as shown in Figure 10. The sheets are composed of unidirectional basalt fibers which are produced by melting and subsequent spinning of volcanic rocks. Polyester threads are used to weave the fabric and prevent frying. The dry fiber properties were provided by the manufacturer and included density, equivalent thickness, ultimate tensile strength, elastic modulus, and ultimate tensile strain of 2.8 g/cm\(^3\), 0.14 mm, 3080 MPa, 95 GPa, and 3.15\%, respectively [37].

![Figure 10: BFRP sheet](image)

### 3.2.4.3 Hybrid laminates

FRP laminates consist of FRP sheets impregnated with an epoxy resin. The appropriate performance of these laminates during use is mainly related to their
mechanical properties. The manufacturer of CFRP and BFRP sheets reported the mechanical properties of the dry fiber as presented in sections 3.2.4.1 and 3.2.4.2. Since the mechanical properties of the dry FRP sheets provided by the manufacturer are much higher than the final composite product [38], tensile coupon tests were conducted on FRP laminate samples to obtain their final mechanical properties. The samples were tested according to ASTM D3039 [39] to determine their strength, elastic modulus, and elongation values.

A total of seven different types of coupon laminates were prepared. Each laminate type represented a certain combination of FRP layers used for strengthening RC beams. For each laminate type, six rectangular specimens were prepared in accordance with ASTM D3039 [39]. All coupon laminates had a width and a gauge length of 40mm and 140mm, respectively. The thickness of the coupon varied between 0.625mm to 1.557mm depending on the type of laminate and number of FRP layers. All coupon laminates were cured for a minimum of one week at room temperature prior to testing. Figure 11 shows a sample of the coupon test specimens.

![Figure 11: FRP coupon specimens](image)

The test specimens were aligned in the testing machine and their fibers were placed in the direction of the tensile force. The tensile test was performed using an INSTRON universal testing machine with a capacity of 100kN. The machine has two grips, where one is adjusted for the length of the specimen, and the other is driven to apply tension. The test was performed at room temperature with a constant cross-speed of approximately 2 mm/min. Strain gauges were attached to the coupon
specimens to obtain strain readings as shown in Figure 12. The testing machine configuration is shown in Figures 13 and 14.
The load and extension readings were obtained for each coupon specimen. The tensile strength of laminates was calculated using Equation (1), where the maximum force was divided by the cross-sectional area. The elastic modulus was obtained by measuring the slope of the linear elastic segment of the stress-strain curve. It was observed that failure of all specimens occurred within the gauge length. Moreover, average values were calculated for thickness, elastic modulus, tensile strength, and ultimate tensile strain for each type of laminate, as shown in Table 3.

\[ \sigma = \frac{P_{\text{max}}}{A} \]  

(1)

where:

\( \sigma = \) Tensile strength, (MPa)

\( P_{\text{max}} = \) Maximum load prior to failure, (N)

\( A = \) Average cross-sectional area, (mm\(^2\))

<table>
<thead>
<tr>
<th>FRP Laminate</th>
<th>Thickness (mm)</th>
<th>Elastic Modulus (GPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Ultimate Tensile Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.63</td>
<td>59.93</td>
<td>781.91</td>
<td>1.74</td>
</tr>
<tr>
<td>B</td>
<td>0.72</td>
<td>19.34</td>
<td>411.27</td>
<td>2.32</td>
</tr>
<tr>
<td>CC</td>
<td>1.23</td>
<td>54.02</td>
<td>706.50</td>
<td>1.77</td>
</tr>
<tr>
<td>BB</td>
<td>1.03</td>
<td>28.02</td>
<td>489.04</td>
<td>2.59</td>
</tr>
<tr>
<td>BC</td>
<td>1.03</td>
<td>47.96</td>
<td>770.01</td>
<td>2.02</td>
</tr>
<tr>
<td>BCC</td>
<td>1.56</td>
<td>46.26</td>
<td>758.63</td>
<td>2.46</td>
</tr>
<tr>
<td>BCB</td>
<td>1.53</td>
<td>41.87</td>
<td>704.02</td>
<td>2.08</td>
</tr>
</tbody>
</table>

Figure 15 shows the stress-strain curves of different FRP laminates. The hybrid system effect is evident from the stress-strain curves. It can be deduced that the CFRP laminate exhibited higher tensile strength and elastic modulus and lower rupture strain than the BFRP laminate. The hybrid laminate combining CFRP and
BFRP sheets (BC) yielded a ductile behavior with enhanced elongation values compared to CFRP laminates, and higher tensile strength values compared to BFRP laminates. In the hybrid system, carbon fibers with high tensile strength and low elongation values will rupture first, while basalt fibers with high elongation values will take the extra load, and hold the progress of carbon fiber rupture. This behavior produces a gradual rupture in the carbon fibers represented by the fluctuating pattern in the stress-strain curve, where the gradual rupture in carbon fibers causes the tensile strength to drop at different intervals, which results in a bilinear stress-strain behavior with increased ductility of the strengthening system.

It is also evident from the stress-strain curves in Figure 15 that as the number of FRP layers in the hybrid combination increases, the behavior of that system changes depending on the type of FRP sheets. When two layers of BFRP sheets and one layer of CFRP sheet (BCB) were tested, the stress-strain curve of this hybrid combination leans closer to the BFRP curve with a lower stiffness value compared to the BC laminate. Quite the reverse, when two layers of CFRP sheets with one layer of BFRP sheet (BCC) were used, the stress-strain curve of this hybrid combination will behave more similarly to the CFRP laminate, and the stiffness value will be higher than the BC laminate.

![Figure 15: FRP coupon test results](image-url)
3.3. Test Setup

All beams were simply supported with an effective span of 1690mm and tested under four point bending until failure. An INSTRON Universal Testing Machine (UTM), with a hydraulic actuator and a maximum capacity of 2500kN, was used to apply a monotonic load and simulate a static loading condition. Flexural tests were displacement controlled with a rate of 2 mm/min applied on the mid-span of the RC beams. The accuracy of the testing machine is ±1% of the reading. Figures 16 and 17 illustrate the test set-up.

![Figure 16: Schematic of flexural test set-up (mm)](image)

![Figure 17: Flexural test set-up](image)
3.4. Test Matrix

A total of ten RC beams were tested. Nine beams were strengthened with different combinations of CFRP and BFRP sheets and one beam was used as a control beam with no strengthening. All FRP sheets used for strengthening covered the full width of the RC beams and 90% of the RC beams’ length with dimensions of 120mm x 1520mm. Table 4 lists all RC beams tested in this research. Beams strengthened with FRP sheets are denoted with C and B, referring to CFRP and BFRP laminates, respectively.

Table 4: Test matrix

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of FRP layers</th>
<th>Strengthening Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>-</td>
<td>No strengthening</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>One layer of CFRP</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>One layer of BFRP</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>Two layers of CFRP</td>
</tr>
<tr>
<td>BB</td>
<td>2</td>
<td>Two layers of BFRP</td>
</tr>
<tr>
<td>BC</td>
<td>2</td>
<td>One layer of BFRP bonded with one layer of CFRP</td>
</tr>
<tr>
<td>CB</td>
<td>2</td>
<td>One layer of CFRP bonded with one layer of BFRP</td>
</tr>
<tr>
<td>CCB</td>
<td>3</td>
<td>Two layers of CFRP and one layer of BFRP; bonded in sequence</td>
</tr>
<tr>
<td>BCC</td>
<td>3</td>
<td>One layer of BFRP and two layers of CFRP; bonded in sequence</td>
</tr>
<tr>
<td>BCB</td>
<td>3</td>
<td>One layer of BFRP, one Layer of CFRP, and one layer of BFRP; bonded in sequence</td>
</tr>
</tbody>
</table>
Chapter 4: Experimental Results and Discussion

This chapter includes the results obtained from the experimental testing of RC beams strengthened with CFRP, BFRP, and their different hybrid combinations. The results include the load versus mid-span deflection curves and the associated failure modes of all RC beams. Also discussed in this chapter is the increase in load bearing capacity and ductility of the strengthened beam and investigates the performance of the hybrid strengthening system. Finally, the results obtained from the experimental testing are summarized and used to compare the performance of different combinations of FRP laminates.

4.1. Load-deflection relationships and failure modes

This section includes the load mid-span deflection relationships for all tested specimens. The test results are used to obtain the ultimate bearing capacity, the ultimate deflection, and deflection at failure of each strengthened beam. The ultimate bearing capacity \( (P_u) \) is the maximum load which the beam can carry before failure. The deflection of the beam corresponding to that load is denoted by the ultimate deflection \( (\delta_{\text{ultimate}}) \). The deflection at failure is defined as the maximum deflection of the RC beam.

The performance of the strengthening system is evaluated by calculating the percent increase in the load bearing capacity and the ductility of the RC beams compared to the un-strengthened beam. The increase in the load bearing capacity is calculated as the ratio of the ultimate load of the strengthened beam to the ultimate load of the control beam.

In order to evaluate the ductility of the tested RC beams, the yield point of steel rebars was considered as a reference point to measure the increase in the system’s ductility. Two ratios were used for ductility evaluation; the ratio of beam deflection at ultimate load to beam deflection at yield point \( (\delta_{\text{ultimate}} / \delta_{\text{yield}}) \), and the ratio of beam deflection at failure load to beam deflection at yield point \( (\delta_{\text{failure}} / \delta_{\text{yield}}) \).

Finally, the failure mode of each RC beam is discussed in this section. Overall, the failure of the strengthened RC beams included flexural cracks, concrete crushing, FRP delamination (concrete cover separation), and FRP rupture.
4.1.1. Control Beam (NS)

The un-strengthened control beam test results were used as a reference point to evaluate the performance of RC beams strengthened with different combinations of CFRP and BFRP sheets. The test results were used to plot the load versus mid-span deflection curve as illustrated in Figure 18. The control beam yielded an ultimate load of 57.3 kN with a corresponding deflection of 34.1 mm. The deflection value at failure was equal to 35.1 mm. The beam failed in a typical flexural mode where there was yielding of the steel rebars followed by crushing of concrete at the top face of the beam in the mid-span region, as shown in Figure 19.

![Figure 18: NS - Load (kN) vs. Deflection (mm)](image)

![Figure 19: Control beam failure (flexural cracks)](image)
4.1.2. Beam (C)

The RC beam strengthened with one layer of CFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as shown in Figure 20. The ultimate load obtained was equal to 89.9 kN with a corresponding deflection of 19.3 mm. The mid-span deflection value at failure was equal to 19.3 mm. The percent increase in the flexural capacity was equal to 57%. The percent decrease in the ultimate and failure ductility values were equal to 52% and 54%, respectively. The beam failed by yielding of the steel rebar followed by FRP delamination (concrete cover separation) as shown in Figure 21.

![Figure 20: C - Load (kN) vs. Deflection (mm)](image1)

![Figure 21: Failure of the strengthened beam (C)](image2)
4.1.3. Beam (CC)

The RC beam strengthened with two layers of CFRP sheets was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 22. The ultimate load obtained was equal to 98.5kN with a corresponding deflection of 14mm. The mid-span deflection value at failure was equal to 14.9mm. The percent increase in the flexural capacity was equal to 72%. The percent decrease in the ultimate and failure ductility values were equal to 67% and 65%, respectively. The beam failed by yielding of the steel rebar followed by FRP delamination (concrete cover separation) as shown in Figure 23.

![Figure 22: CC - Load (kN) vs. Deflection (mm)](image)

![Figure 23: Failure of the strengthened beam (CC)](image)
4.1.4. Beam (B)

The RC beam strengthened with one layer of BFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 24. The ultimate load obtained was equal to 73.4 kN with a corresponding deflection of 22.2mm. The mid-span deflection value at failure was equal to 23.7mm. The percent increase in the flexural capacity was equal to 28%. The percent decrease in the ultimate and failure ductility values were equal to 40% and 37%, respectively. The beam failed by yielding of the steel rebar followed by FRP rupture as shown in Figure 25.

![Figure 24: B - Load (kN) vs. Deflection (mm)](image1)

![Figure 25: Failure of the strengthened beam (B)](image2)
4.1.5. Beam (BB)

The RC beam strengthened with two layers of BFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 26. The ultimate load obtained was equal to 93kN with a corresponding deflection of 28mm. The mid-span deflection value at failure was equal to 28.6mm. The percent increase in the flexural capacity was equal to 62%. The percent decrease in the ultimate and failure ductility values were equal to 31%. The beam failed by yielding of the steel rebar, followed by rupture of the FRP sheet, and crushing of concrete at the loading point as shown in Figure 27.

Figure 26: BB - Load (kN) vs. Deflection (mm)

Figure 27: Failure of the strengthened beam (BB)
4.1.6. Beam (BC)

The RC beam strengthened with one layer of BFRP sheet and one layer of CFRP was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 28. The ultimate load obtained was equal to 95.8 kN with a corresponding deflection of 16.3mm. The mid-span deflection value at failure was equal to 16.6mm. The percent increase in the flexural capacity was equal to 67%. The percent decrease in the ultimate and failure ductility values were equal to 60% and 61%, respectively. The beam failed by yielding of the steel rebar with major flexural cracks followed by FRP delamination (concrete cover separation) as shown in Figure 29.

Figure 28: BC - Load (kN) vs. Deflection (mm)

Figure 29: Failure of the strengthened beam (BC)
4.1.7. Beam (CB)

The RC beam strengthened with one layer of CFRP sheet and one layer of BFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 30. The ultimate load obtained was equal to 95.3kN with a corresponding deflection of 15.7mm. The mid-span deflection value at failure was equal to 16mm. The percent increase in the flexural capacity was equal to 66%. The percent decrease in the ultimate and failure ductility values were equal to 62%. The beam failed by steel yielding with major flexural cracks followed by FRP delamination (concrete cover separation) as shown in Figure 31.

![Figure 30: CB - Load (kN) vs. Deflection (mm)](image)

![Figure 31: Failure of the strengthened beam (CB)](image)
4.1.8. Beam (CCB)

The RC beam strengthened with two layers of CFRP sheet and one layer of BFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 32. The ultimate load obtained was equal to 100.5kN with a corresponding deflection of 12.5mm. The mid-span deflection value at failure was equal to 13mm. The percent increase in the flexural capacity was equal to 75%. The percent decrease in the ultimate and failure ductility values were equal to 71%. The beam failed by steel yielding followed by FRP delamination (concrete cover separation) as shown in Figure 33.

![Graph: Load (kN) vs. Deflection (mm)](image1)

Figure 32: CCB - Load (kN) vs. Deflection (mm)

![Image: Failure of the strengthened beam (CCB)](image2)

Figure 33: Failure of the strengthened beam (CCB)
4.1.9. Beam (BCC)

The RC beam strengthened with one layer of BFRP sheet and two layers of CFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 34. The ultimate load obtained was equal to 96.8 kN with a corresponding deflection of 12.8mm. The mid-span deflection value at failure was equal to 13.3mm. The percent increase in the flexural capacity was equal to 69%. The percent decrease in the ultimate and failure ductility values were equal to 71% and 70%, respectively. The beam failed by steel yielding followed by FRP delamination (concrete cover separation) as shown in Figure 35.

![Figure 34: BCC - Load (kN) vs. Deflection (mm)](image)

![Figure 35: Failure of the strengthened beam (BCC)](image)
4.1.10. Beam (BCB)

The RC beam strengthened with two layers of BFRP sheet and one layer of CFRP sheet was tested until failure. The load versus mid-span deflection readings were obtained from the test as illustrated in Figure 36. The ultimate load obtained was equal to 100.3 kN with a corresponding deflection of 15.8mm. The mid-span deflection value at failure was equal to 15.9mm. The percent increase in the flexural capacity was equal to 75%. The percent decrease in the ultimate and failure ductility values were equal to 62% and 63%, respectively. The beam failed by steel yielding followed by FRP delamination (concrete cover separation) as shown in Figure 37.

![Figure 36: BCB - Load (kN) vs. Deflection (mm)](image)

![Figure 37: Failure of the strengthened beam (BCB)](image)
4.2. **Discussion of results**

This section summarizes the results obtained from the experimental testing of RC beams. Figure 38 illustrates the different behavior of beams strengthened with different combinations of FRP laminates.

![Figure 38: Load (kN) vs. Deflection (mm) of all tested beams](image)

It is clear from Figure 38 that the beams strengthened with FRP sheets provided higher flexural bearing capacity, yet lower deflection values than that of the un-strengthened beam.

The experimental results including the ultimate load \( (P_u) \), ratio of the ultimate load of the strengthened beam to the ultimate load of the control beam \( (P_u / P_{u,NS}) \), ratio of the ultimate load of the strengthened beam to the ultimate load of the beam strengthened with one layer of CFRP \( (P_u / P_{u,C}) \), and the associated failure mode are summarized in Table 5.
Table 5: Summary of ultimate loads and failure modes

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$P_u$ (kN)</th>
<th>$P_u / P_{u,NS}$</th>
<th>$P_u / P_{u,C}$</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>57.32</td>
<td>-</td>
<td>-</td>
<td>Flexural failure, steel yielding followed by concrete crushing</td>
</tr>
<tr>
<td>C</td>
<td>89.87</td>
<td>1.57</td>
<td>-</td>
<td>Steel yielding followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>CC</td>
<td>98.45</td>
<td>1.72</td>
<td>1.10</td>
<td>Steel yielding followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>B</td>
<td>73.37</td>
<td>1.28</td>
<td>0.82</td>
<td>Steel yielding followed by FRP rupture</td>
</tr>
<tr>
<td>BB</td>
<td>93.07</td>
<td>1.62</td>
<td>1.04</td>
<td>Steel yielding followed by FRP rupture and concrete crushing at loading support</td>
</tr>
<tr>
<td>BC</td>
<td>95.77</td>
<td>1.67</td>
<td>1.07</td>
<td>Steel yielding with major flexural cracks followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>CB</td>
<td>95.27</td>
<td>1.66</td>
<td>1.06</td>
<td>Steel yielding with major flexural cracks followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>CCB</td>
<td>100.52</td>
<td>1.75</td>
<td>1.12</td>
<td>Steel yielding followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>BCC</td>
<td>96.78</td>
<td>1.69</td>
<td>1.08</td>
<td>Steel yielding followed by FRP delamination (concrete cover separation)</td>
</tr>
<tr>
<td>BCB</td>
<td>100.32</td>
<td>1.75</td>
<td>1.12</td>
<td>Steel yielding followed by FRP delamination (concrete cover separation)</td>
</tr>
</tbody>
</table>

It can be noticed from Figure 38 and Table 5 that the increase in the flexural capacity of strengthened beams ranged from 28% to 75% of the control beam. It can also be noticed that beams strengthened with CCB and BCB yielded the highest increase in flexural capacity (75%). Moreover, these beams were 12% higher in flexural capacity than those strengthened with CFRP sheets only.

By comparing the failure modes of different strengthened beams in Table 5, it can be noticed that RC beams strengthened with one layer and two layers of BFRP sheets had the best mode of failure. These beams failed by BFRP sheet rupture, which indicates that the maximum capacity of BFRP sheets was achieved and the strengthening system was fully utilized.

Table 6 summarizes the ductility indices measured for all RC beams. The table shows two indices; the ultimate deflection index $I_u$, which is the ratio of the beam deflection at ultimate load to the beam deflection at steel yield point ($\delta_{\text{ultimate}} / \delta_{\text{yield}}$), and the failure deflection index $I_f$, which is the ratio of the beam deflection at failure load to the beam deflection at steel yield point ($\delta_{\text{failure}} / \delta_{\text{yield}}$). Table 6 also
presents the ductility ratios to compare the flexural performance of the strengthened beams to that of the control beam.

Table 6: Summary of the deflection values and ductility results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\delta_y$ (mm)</th>
<th>$\delta_u$ (mm)</th>
<th>$\delta_f$ (mm)</th>
<th>$I_u = \frac{\delta_u}{\delta_y}$</th>
<th>$I_u/I_{u,NS}$</th>
<th>% decrease</th>
<th>$I_f = \frac{\delta_f}{\delta_y}$</th>
<th>$I_f/I_{f,NS}$</th>
<th>% decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
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<td>0.63</td>
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<td>0.69</td>
<td>31</td>
<td>3.72</td>
<td>0.69</td>
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<td>16.55</td>
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<td>60</td>
<td>2.12</td>
<td>0.39</td>
<td>61</td>
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<td>0.38</td>
<td>62</td>
<td>1.99</td>
<td>0.37</td>
<td>63</td>
</tr>
</tbody>
</table>

It can be noticed from Table 6 that the beams strengthened with FRP sheets exhibited 31% to 71% lower ductility at ultimate load than that of the un-strengthened beam, and 31% to 71% lower ductility at failure load than that of the un-strengthened beam. The beam strengthened with two layers on BFRP sheets (BB) had the highest ductility among all strengthened beams with 31% reduction in RC beam ductility compared to the un-strengthened beam.

The effect of combining CFRP and BFRP sheets is illustrated in Figure 39. The figure compares the flexural performance of three RC beams. The first RC beam was strengthened with two layers of CFRP sheets (CC), the second beam was strengthened with two layers of BFRP sheets (BB), and the third beam was strengthened with the hybrid combination of CFRP and BFRP sheets (BC). It can be noticed that the beam strengthened with two layers of CFRP sheet (CC) presented the
highest flexural capacity and the lowest ductility. In contrast, the RC beam strengthened with two layers of BFRP sheet (BB) showed the highest ductility and the lowest flexural capacity. On the other hand, the RC beam strengthened with the hybrid combination of CFRP and BFRP sheets presented higher flexural capacity than the beam strengthened with BFRP and higher ductility than the beam strengthened with CFRP. Thus, it can be concluded that the hybrid combination of CFRP and BFRP sheets provides an enhanced strengthening system, where it combines the high strength of CFRP sheets and the high ductility of BFRP sheets.

![Figure 39: Hybrid system performance](image)

Figure 40 shows the load versus mid-span deflection curves of the beams strengthened with the hybrid CFRP-BFRP sheets. It can be noticed that interchanging the sequence of FRP sheets did not have an impact on the behavior of the strengthened beam. Beams strengthened with CB and BC yielded the same results for strength and ductility. Both beams had an increase in flexural capacity of 67% compared to the un-strengthened beam. Moreover, both beams had the same reduction in beam ductility (61%) compared to the un-strengthened beam.

The same observation was made from the beams strengthened with three layers of FRP sheets. Figure 41 shows that the beams strengthened with CCB and BCC presented the same increase in flexural capacity and an equal reduction in beam ductility. Both beams had an increase in flexural capacity of 72% and decrease in
flexural ductility of 71%. However when the beam was strengthened with BCB, more ductility was observed, where the reduction in flexural ductility was 62%.

Figure 40: Load vs. deflection – Beams strengthened with 2 layers of FRP sheets

Figure 41: Load vs. deflection – Beams strengthened with 3 layers of FRP sheets
Chapter 5: Finite Element Modeling

This chapter presents the use of Finite Element (FE) modeling to analyze the behavior of the experimentally tested specimens reported in Chapter 4. Finite element modeling is a powerful tool to investigate the flexural performance of RC beams strengthened by the proposed hybrid CFRP-BFRP system. The multipurpose software ANSYS [40] was used to develop eight FE models representing eight different FRP strengthening schemes. The developed models incorporate a high level of nonlinearity and complexity by considering the performance of the concrete in tension (cracking) and compression (stress-strain curve), yielding of steel reinforcement, orthotropic material properties of the FRP materials, and debonding at the concrete-FRP interface.

This chapter describes the FE model creation in detail and explains the element types, constitutive material properties, geometry, loading and boundary conditions used in developing the FE models.

5.1. Element types and material constitutive models

5.1.1. Concrete element

A 3D Reinforced Concrete Solid, SOLID65 [40] element was used to model the concrete material. The brick element has eight nodes with 3 degrees of freedom per node and is capable of cracking in three orthogonal directions [40]. The material properties assigned to concrete were obtained from the experimental testing presented in Chapter 3. The concrete compressive strength, elastic modulus and Poisson ratio were assigned as 38.78 MPa, 29.27 GPa and 0.2, respectively.

Figure 42: ANSYS Concrete Brick element, SOLID65 Geometry [40]
Mathematical expressions were employed to model the nonlinear behavior of concrete under compression and tension. Hognestad parabola with a linear descending branch [41] was used to obtain the nonlinear stress-strain curve of concrete under a uniaxial compression force as presented in Equations (2) and (3). Figure 43 is a schematic representation of the concrete stress-strain curve obtained using the Hognestd parabola.

\[
f_c = f_c \left[ \frac{2e_c}{e_{co}} - \left( \frac{e_c}{e_{co}} \right)^2 \right] \quad \text{for} \quad 0 \leq e_c \leq e_{co}
\]

\[
f_c = f'_c - \frac{0.15f'_c}{e_{co} - e_{co}} (e_c - e_{co}) \quad \text{for} \quad e_c > e_{co}
\]

where:
- \(f_c\) = concrete compressive stress (MPa)
- \(f'_c\) = concrete compressive strength (MPa)
- \(e_c\) = concrete strain ratio
- \(e_{co}\) = concrete strain corresponding to \(f'_c\)

![Figure 43: Concrete compressive stress strain curve](image)

The concrete stress-strain curve under tensile force was obtained using William and Warnke equations [42]. The concrete tensile strength was obtained using Equation (4) [43]. The concrete tensile behavior was modeled as a linear elastic
response until reaching the maximum tensile strength with a strain $\varepsilon_t$ obtained using Equation (5). After that, the concrete cracks and the tensile strength drops vertically to 60% of its value followed by a linear decrease in the tensile stress, where it reaches zero stress at a strain value equal to 6$\varepsilon_t$. Figure 44 illustrates the concrete stress-strain behavior in tension using William and Warnke equations [42].

$$f_t = 0.62 \sqrt{f'_c} \tag{4}$$

$$\varepsilon_t = \frac{f_t}{E} \tag{5}$$

where:

- $f_t$ = concrete tensile strength (MPa)
- $f'_c$ = concrete compressive strength (MPa)
- $\varepsilon_t$ = concrete tensile strain ratio
- $E$ = elastic modulus of concrete (MPa)

![Figure 44: Concrete tensile stress strain curve](image)

In addition, SOLID65 requires including a shear transfer coefficient value, $\beta_t$. The coefficient ranges from 0 to 1, with 0 for a smooth crack and no shear transfer, and 1 for a rough crack with full shear transfer [40]. Studies have shown that the shear transfer coefficient values less than 0.2 caused a solution convergence problem. Therefore, in this study, the shear coefficient value assigned was equal to 0.2.
5.1.2. Steel rebar element

Longitudinal steel reinforcement and stirrups were modeled using the ANSYS 3D Spar LINK8 [40] elements. The element has two nodes with translational 3 degrees of freedom per node and is capable of plastic deformation, creep, swelling, and stress stiffening [40]. The material properties assigned to the steel reinforcement were obtained from the experimental testing presented in Chapter 3. The steel yield strength, elastic modulus and Poisson ratio were taken as 540 MPa, 200 GPa and 0.3, respectively. The nonlinear behavior of steel was modeled as elastic-perfectly plastic, both in tension and compression as shown in Figure 41.

Figure 45: ANSYS Spar element, LINK8 Geometry [40]

Figure 46: Steel elastic-perfectly plastic model

5.1.3. Support and loading points element

ANSYS 3D Structural Solid, SOLID45 [40] elements were used to simulate rigid steel supports and loading pedestals used during the four-point bending test of RC beam specimens. These elements provide a uniform stress distribution over the
support and loading areas. SOLID45 is similar to SOLID65 but without the cracking capability. The material is defined as a rigid elastic material with a modulus of elasticity and Poisson ratio of 200 GPa and 0.3, respectively. The specimens were analyzed as simply supported beams.

![Figure 47: ANSYS Brick element, SOLID45 Geometry [40]](image)

5.1.4. FRP laminates element

ANSYS Elastic Shell, SHELL63 [40] element was used to model different combinations of FRP laminates. The element has 4 nodes with 6 degrees of freedom per node [40]. SHELL63 has orthotropic material properties with stress stiffening, bending and large deflection capabilities [40]. FRP sheets are orthotropic materials, which means they have different mechanical properties along different directions. The material properties in the x direction (fiber direction) were obtained from coupon tests as described in Chapter 3, Section 3.2.4.3. The mechanical properties of FRP materials in the y and z directions (perpendicular to the fiber direction) were obtained using Equations (6) and (7). Table 7 summarizes the mechanical properties assigned to the FRP elements.
Figure 48: ANSYS Elastic shell element, SHELL63 Geometry [35]

\[ G_{xy} = \frac{E_y}{2(1 + \nu_{xy})} \]  

\[ G_{xz} = \frac{E_z}{2(1 + \nu_{xz})} \]

where:

- \( E_x \) = Elastic modulus in the x direction (GPa)
- \( E_y \) = Elastic modulus in the y direction (GPa)
- \( E_z \) = Elastic modulus in the z direction (GPa)
- \( \nu_{xy} \) = Major Poisson’s ratio in the xy plane
- \( \nu_{xz} \) = Major Poisson’s ratio in the xz plane
- \( \nu_{yz} \) = Major Poisson’s ratio in the yz plane
- \( G_{xy} \) = Shear modulus in the xy plane (GPa)
- \( G_{xz} \) = Shear modulus in the xz plane (GPa)
- \( G_{yz} \) = Shear modulus in the yz plane (GPa)
Table 7: FRP mechanical properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>$E_x$ (GPa)</th>
<th>$E_y = E_z$ (GPa)</th>
<th>$\nu_{xy} = \nu_{xz}$</th>
<th>$\nu_{yz}$</th>
<th>$G_{xy} = G_{xz}$ (GPa)</th>
<th>$G_{yz}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.63</td>
<td>49.94</td>
<td>3.50</td>
<td>0.28</td>
<td>0.42</td>
<td>1.37</td>
<td>1.23</td>
</tr>
<tr>
<td>B</td>
<td>0.72</td>
<td>17.79</td>
<td>1.25</td>
<td>0.15</td>
<td>0.21</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>CC</td>
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<td>46.05</td>
<td>3.22</td>
<td>0.28</td>
<td>0.42</td>
<td>1.26</td>
<td>1.14</td>
</tr>
<tr>
<td>BB</td>
<td>1.03</td>
<td>24.98</td>
<td>1.75</td>
<td>0.15</td>
<td>0.21</td>
<td>0.76</td>
<td>0.72</td>
</tr>
<tr>
<td>BC</td>
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<td>0.22</td>
<td>0.32</td>
<td>1.31</td>
<td>1.21</td>
</tr>
<tr>
<td>BCC</td>
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<td>38.91</td>
<td>2.72</td>
<td>0.24</td>
<td>0.35</td>
<td>1.01</td>
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</tr>
<tr>
<td>BCB</td>
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<td>37.81</td>
<td>2.65</td>
<td>0.19</td>
<td>0.28</td>
<td>1.11</td>
<td>1.03</td>
</tr>
</tbody>
</table>

5.1.5. Concrete- FRP Interface element

ANSYS 3D Cohesive elements, INTER205 [40] were used to simulate the possibility of composite sheet debonding from the soffit of the concrete beams. INTER205 is a linear interface element with 8 nodes and 3 degrees of freedom at each node (transition in x, y and z directions) [40]. This element is used to represent the interface between concrete elements (SOLID65) and FRP laminates (SHELL63). It simulates the debonding process though increased displacement values between nodes within INTER205 elements itself [40].

![ANSYS Linear interface element, INTER205 Geometry](image)

Figure 49: ANSYS Linear interface element, INTER205 Geometry [40]

Lu et al. mathematical model [44] was used to accurately predict the bond strength and strain distribution in the FRP laminates. The bond-slip behavior of the interface is represented in terms of shear stresses and corresponding slip values as
obtained from Equations (8) to (13). Figure 50 is a schematic representation of the interface slip model obtained using Lu et al. equations [44].

\[
\tau = \begin{cases} 
\tau_{max} \frac{s}{s_0} & \text{when } s \leq s_0 \\
\tau_{max} e^{-\alpha \left( \frac{s}{s_0} - 1 \right)} & \text{when } s > s_0
\end{cases}
\]  

(8)

\[\tau_{max} = 1.5 \beta_w f_t\]  

(9)

\[s_o = 0.0195 \beta_w^2 f_t\]  

(10)

\[\alpha = \frac{1}{G_f} \left( \frac{2}{\tau_{max} s_0} - \frac{2}{3} \right)\]  

(11)

\[G_f = 0.308 \beta_w^2 \sqrt{f_t}\]  

(12)

\[\beta_w = \sqrt{\frac{2.25 - \frac{b_f}{b_t}}{1.25 + \frac{b_f}{b_t}}}\]  

(13)

where:

\(\tau_{max}\) = Maximal local bond stress (MPa)

\(s\) = slip between the concrete and FRP sheet (mm)

\(s_o\) = local slip at \(\tau_{max}\) (mm)

\(\beta_w\) = width ratio factor

\(\alpha\) = factor depends on interfacial fracture energy, bond strength, and slip at peak

\(G_f\) = interfacial fracture energy

\(b_f\) = width of FRP sheet (mm)

\(b_c\) = width of concrete section (mm)

\(f_t\) = concrete tensile strength (MPa)
5.2. Model creation

A total of 8 FE models were created using ANSYS 11.0 [40]. Table 8 lists the FE models developed in this study along with their designations. Each FE model represents a different strengthening scheme. All beams had the same geometry. The geometry of FE models reflects the real geometry of the tested specimen presented in Chapter 3. The tested specimen had a length of 1840mm, width of 240mm, and a height of 120mm. Two deformed steel rebars placed at an effective depth of 202mm were used for tension reinforcement. The shear reinforcement included 8mm diameter steel rebars with 80mm center-to-center spacing. The strengthened specimens had FRP sheets attached to the tension face of the RC beam. Taking advantage of symmetry in geometry, material properties, loading and boundary conditions, a quarter models of the tested specimens were developed that led to a tremendous savings in computational time. Figure 51 and Figure 52 illustrate the details of the quarter FE model.
Table 8: List of FE models

<table>
<thead>
<tr>
<th>Beam</th>
<th>FE model designation</th>
<th>Strengthening Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>FE-NS</td>
<td>Control Beam</td>
</tr>
<tr>
<td>C</td>
<td>FE-C</td>
<td>Beam Strengthened with one layer of CFRP</td>
</tr>
<tr>
<td>CC</td>
<td>FE-CC</td>
<td>Beam Strengthened with two layers of CFRP</td>
</tr>
<tr>
<td>B</td>
<td>FE-B</td>
<td>Beam Strengthened with one layer of BFRP</td>
</tr>
<tr>
<td>BB</td>
<td>FE-BB</td>
<td>Beam Strengthened with two layers of BFRP</td>
</tr>
<tr>
<td>BC</td>
<td>FE-BC</td>
<td>Beam Strengthened with one layer of BFRP bonded with one layer of CFRP</td>
</tr>
<tr>
<td>BCC</td>
<td>FE-BCC</td>
<td>Beam Strengthened with one layer of BFRP and two layers of CFRP; bonded in sequence</td>
</tr>
<tr>
<td>BCB</td>
<td>FE-BCB</td>
<td>Beam Strengthened with one layer of BFRP, one layer of CFRP, and one layer of BFRP; bonded in sequence</td>
</tr>
</tbody>
</table>

Figure 51: FE model details

Figure 52: Quarter FE model with dimensions (mm)
Chapter 6: Finite Element Results and Discussion

6.1. FE model validation

In this chapter, the predicted ultimate load \( P_u \) along with the associated deflection \( \delta_f \) results are validated against the experimental results. The predicted and measured load versus mid-span deflection responses are shown in Figure 53. It can be noticed that the FE models closely predict the experimental values at all stages of loading for the tested beams presented in this study.

(a) Control Beam
(b) FE-C
(c) FE-CC

(d) FE-B

Axial load (kN) vs. Deflection (mm) for FE and Experimental models.
(e) FE-BB

(f) FE-BC
Table 9 summarizes the results of the experimental testing and the FE analysis for all specimens. The comparison shows that the predicted ultimate load values differ by 1-11% from the experimental values. Besides, the difference between mid-span deflection values at failure obtained from the experimental testing and numerical
simulation are between 1-12% only. Therefore, it was concluded that the developed FE models are valid to predict the response of RC beams strengthened in flexure with externally bonded CFRP sheets, BFRP sheets, and their hybrid combination.

Table 9: FE models validation

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate Load (kN)</th>
<th>Deflection at failure [δf] (mm)</th>
<th>Pu FE/Pu Exp</th>
<th>δf FE/δf Exp</th>
</tr>
</thead>
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<td>Exp.</td>
<td>FE</td>
<td>Exp.</td>
<td>FE</td>
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<td>95.88</td>
<td>19.33</td>
<td>21.52</td>
</tr>
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<td>CC</td>
<td>98.45</td>
<td>108.43</td>
<td>14.93</td>
<td>15.62</td>
</tr>
<tr>
<td>B</td>
<td>73.37</td>
<td>74.77</td>
<td>23.68</td>
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</tr>
<tr>
<td>BB</td>
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</tr>
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<td>BC</td>
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<td>101.69</td>
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<td>101.69</td>
<td>15.95</td>
<td>17.85</td>
</tr>
<tr>
<td>CCB</td>
<td>100.52</td>
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<td>14.17</td>
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<tr>
<td>BCB</td>
<td>100.32</td>
<td>108.13</td>
<td>15.91</td>
<td>16.18</td>
</tr>
</tbody>
</table>

6.2. FE model behavior

The most important advantage of FE modeling over experimental testing is that FE models can help in investigating different output results that cannot be measured experimentally, including stress and strain values at different locations along the beam.

6.2.1. Beam deflections

Figure 54 shows contour plots of nodal displacement values of the beam specimens at failure. Since a quarter FE model was used, the maximum vertical displacement value was reported at the right-side edge of the FE model, which represents the mid-span deflection value of the full size beam.
The RC beam strengthened with two layers of BFRP sheets (FE-BB) showed the maximum mid-span deflection value (29.73mm) at failure load. On the other hand, the RC beam strengthened with one layer of BFRP sheet and two layers of CFRP sheet (FE-BCC) yielded the minimum mid-span deflection value (14.17mm) at failure load.
6.2.2. Stresses in concrete

Figures 55 to 62 show the axial stress along the longitudinal direction of the beam ($S_x$) and the principal stresses ($\sigma_1$ and $\sigma_3$) for each modeled specimen. The first principal stress ($\sigma_1$) and the third principal stress ($\sigma_3$) correspond to the maximum tension and compression stresses, respectively.

It can be noticed that the contour plot of the first principal stress ($\sigma_1$) shows maximum tension stresses at the bottom face of the FE model. Moreover, the contour plot of the third principle stress ($\sigma_3$) shows a high concentration of compressive stresses at the top face of the FE model.
Figure 55: Stress in concrete – Control beam
Figure 56: Stress in concrete – FE- C
Figure 57: Stress in concrete – FE-CC
Figure 58: Stress in concrete – FE-B
Figure 59: Stress in concrete – FE- BB
(a) Stress in the x-direction ($S_x$)

(b) 1st Principle stress ($\sigma_1$)

(c) 3rd Principle stress ($\sigma_3$)

Figure 60: Stress in concrete – FE- BC
Figure 61: Stress in concrete – FE- BCC
(a) Stress in the x-direction ($S_x$)

(b) 1st Principle stress ($\sigma_1$)

(c) 3rd Principle stress ($\sigma_3$)

Figure 62: Stress in concrete – FE-BCB
6.2.3. Stresses in steel rebars

Figure 63 shows the axial stress values in the steel rebars at the yield point for each beam specimen. The upper contour line which represents the top steel reinforcement showed negative stress values indicating compressive stresses. Similarly, the lower contour line which represents the bottom steel reinforcement showed positive stress values indicating tensile stresses. Moreover, it can be noticed that the stresses in the steel rebar of all beam specimens reached the yield strength of 540 MPa prior to failure load. Figure 63 shows the load at which the steel rebar has reached the yield point.

\[ P_y = 51.91 \text{ kN} \quad \text{(a) Control beam} \]

\[ P_y = 64.23 \text{ kN} \quad \text{(b) FE-C} \]

\[ P_y = 71.73 \text{ kN} \quad \text{(c) FE-CC} \]

\[ P_y = 57.26 \text{ kN} \quad \text{(d) FE-B} \]
Table 10 compares the load and deflection values at which the steel rebars reached the yield point in the experimental testing and FE modeling. The stiffness of the beam (k) is calculated as the ratio of the load to the deflection at yield point. The stiffness values obtained from the experimental testing were compared to the values obtained from the FE modeling. Table 10 shows that the FE model behavior was stiffer than the experimental one. The increase in stiffness was in the range of 1% to 13%.

Figure 63: Stress in Steel rebars at yield point
Table 10: Steel yield point - Experimental versus FE

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Experimental</th>
<th>FE</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_y$ (kN)</td>
<td>$\delta_y$ (mm)</td>
<td>$k_{Exp} = \frac{P_y}{\delta_y}$</td>
<td>$P_y$ (kN)</td>
<td>$\delta_y$ (mm)</td>
<td>$k_{FE} = \frac{P_y}{\delta_y}$</td>
</tr>
<tr>
<td>NS</td>
<td>52.00</td>
<td>6.50</td>
<td>8.00</td>
<td>51.91</td>
<td>6.34</td>
<td>8.19</td>
</tr>
<tr>
<td>C</td>
<td>72.00</td>
<td>7.70</td>
<td>9.35</td>
<td>64.26</td>
<td>6.34</td>
<td>10.14</td>
</tr>
<tr>
<td>CC</td>
<td>83.00</td>
<td>8.00</td>
<td>10.38</td>
<td>71.73</td>
<td>6.34</td>
<td>11.31</td>
</tr>
<tr>
<td>B</td>
<td>57.00</td>
<td>7.00</td>
<td>8.14</td>
<td>57.26</td>
<td>6.34</td>
<td>9.03</td>
</tr>
<tr>
<td>BB</td>
<td>73.00</td>
<td>7.70</td>
<td>9.48</td>
<td>60.41</td>
<td>6.34</td>
<td>9.53</td>
</tr>
<tr>
<td>BC</td>
<td>75.00</td>
<td>7.80</td>
<td>9.62</td>
<td>67.19</td>
<td>6.34</td>
<td>10.60</td>
</tr>
<tr>
<td>BCC</td>
<td>84.00</td>
<td>8.30</td>
<td>10.12</td>
<td>72.66</td>
<td>6.34</td>
<td>11.46</td>
</tr>
<tr>
<td>BCB</td>
<td>81.00</td>
<td>8.00</td>
<td>10.13</td>
<td>69.58</td>
<td>6.34</td>
<td>10.97</td>
</tr>
</tbody>
</table>

6.2.4. Stress and strain in FRP sheets

FE models can be used to obtain stresses and strain values at different locations along the modeled specimen. In this section, the FE models were used to obtain the axial and shear stress and strain values along the FRP elements. The axial stress and strain values obtained from the FE simulation were compared to the average values of ultimate tensile strength obtained from the coupon tests which are described in Chapter 3, Section 3.2.4.3. Moreover, the shear stress and strain values of FRP elements were compared to the maximum shear strength of the bond-slip model which was presented in Chapter 5, Section 5.1.5.

Table 11 shows a comparison of axial stress and strain values obtained from the experimental testing versus FE modeling. It can be noticed that the predicted axial stress and strain values exceeded the experimental ones for the beams strengthened with one layer and two layers of BFRP sheets. This explains the rupture of BFRP laminates during the experimental testing as illustrated in Chapter 4, Sections 4.1.4 and 4.1.5.
Table 11: Stress and strain in FRP sheets

<table>
<thead>
<tr>
<th>FRP Laminate</th>
<th>Ultimate Tensile Stress (MPa)</th>
<th>Ultimate Tensile Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>FE</td>
</tr>
<tr>
<td>C</td>
<td>781.91</td>
<td>711.82</td>
</tr>
<tr>
<td>CC</td>
<td>706.50</td>
<td>490.05</td>
</tr>
<tr>
<td>B</td>
<td>411.27</td>
<td>429.94</td>
</tr>
<tr>
<td>BB</td>
<td>489.04</td>
<td>490.01</td>
</tr>
<tr>
<td>BC</td>
<td>770.01</td>
<td>502.06</td>
</tr>
<tr>
<td>BCC</td>
<td>758.63</td>
<td>380.09</td>
</tr>
<tr>
<td>BCB</td>
<td>704.02</td>
<td>373.77</td>
</tr>
</tbody>
</table>

The contour plots of shear stresses in each FRP laminate are also presented in Figures 64 to 70. The maximum shear stress reported in each contour plot was compared to the maximum stress of the bond-slip model presented in Chapter 5, Section 5.1.5. Looking at the predicted values of the maximum shear stress, it can be noticed that the maximum bond stress (4.5MPa) which causes debonding of FRP laminates from the soffit of the RC beam was not exceeded in all modeled specimens. Consequently, this verifies that FE models can be used to predict the failure mode of the strengthened beams.
Figure 64: Stress and strain in FRP sheet (FE-C)
Figure 65: Stress and strain in FRP sheet (FE-CC)
Figure 66: Stress and strain in FRP sheet (FE-B)
Figure 67: Stress and strain in FRP sheet (FE-BB)
Figure 68: Stress and strain in FRP sheet (FE-BC)
Figure 69: Stress and strain in FRP sheet (FE-BCC)
6.2.5. Crack Propagation

Figures 71 to 78 show the predicted crack propagation of all specimens at certain applied displacement values. It can be noticed that the flexural cracks in all the beams initiated from the mid-span of the beam. Moreover, the failure mode of all the beams could be predicted from the excessive concentration of flexural cracks at the bottom face of the beam, which indicated the possibility of concrete cover separation (delamination).
Load Step 2
Deflection= 0.98 mm
Load= 13.46 kN

Load Step 4
Deflection= 2.74 mm
Load= 27.72 kN

Load Step 7
Deflection= 6.37 mm
Load= 51.91 kN

Load Step 10
Deflection= 10.11 mm
Load= 54.23 kN

Load Step 14
Deflection= 14.65 mm
Load= 56.40 kN

Load Step 20
Deflection= 35.13 mm
Load= 56.08 kN

Figure 71: Crack propagation at different load steps – FE- Control Beam
Load Step 2
Deflection = 0.97 mm
Load = 16.06 kN

Load Step 4
Deflection = 2.75 mm
Load = 32.46 kN

Load Step 6
Deflection = 4.85 mm
Load = 52.02 kN

Load Step 9
Deflection = 8.42 mm
Load = 72.11 kN

Load Step 13
Deflection = 13.11 mm
Load = 83.80 kN

Load Step 17
Deflection = 21.52 mm
Load = 95.88 kN

Figure 72: Crack propagation at different load steps – FE-C
Load Step 2
Deflection= 0.96 mm
Load= 18.31 kN

Load Step 4
Deflection= 2.74 mm
Load= 35.57 kN

Load Step 6
Deflection= 4.84 mm
Load= 57.45 kN

Load Step 9
Deflection= 8.32 mm
Load= 82.26 kN

Load Step 13
Deflection= 12.90 mm
Load= 100.09 kN

Load Step 15
Deflection= 15.62 mm
Load= 108.43 kN

Figure 73: Crack propagation at different load steps – FE- CC
Load Step 2
Deflection= 0.98 mm
Load= 15.17 kN

Load Step 4
Deflection= 2.75 mm
Load= 29.26 kN

Load Step 6
Deflection= 4.85 mm
Load= 47.28 kN

Load Step 9
Deflection= 8.46 mm
Load= 60.93 kN

Load Step 13
Deflection= 13.34 mm
Load= 67.22 kN

Load Step 18
Deflection= 25.18 mm
Load= 74.77 kN

Figure 74: Crack propagation at different load steps – FE- B
Load Step 2
Deflection= 0.99 mm
Load= 15.11 kN

Load Step 4
Deflection= 2.79 mm
Load= 29.06 kN

Load Step 6
Deflection= 4.95 mm
Load= 47.18 kN

Load Step 9
Deflection= 8.96 mm
Load= 60.83 kN

Load Step 14
Deflection= 14.21 mm
Load= 77.60 kN

Load Step 20
Deflection= 29.73 mm
Load= 95.01 kN

Figure 75: Crack propagation at different load steps – FE- BB
Load Step 2
Deflection= 1.01 mm
Load= 19.82 kN

Load Step 4
Deflection= 2.75 mm
Load= 34.32 kN

Load Step 6
Deflection= 4.83 mm
Load= 54.26 kN

Load Step 9
Deflection= 8.34 mm
Load= 75.22 kN

Load Step 13
Deflection= 12.98 mm
Load= 89.92 kN

Load Step 17
Deflection= 17.85 mm
Load= 101.69 kN

Figure 76: Crack propagation at different load steps – FE- BC
Load Step 2
Deflection= 0.99mm
Load= 17.05 kN

Load Step 4
Deflection=2.77 mm
Load=36.63 kN

Load Step 6
Deflection= 4.85 mm
Load= 58.33 kN

Load Step 9
Deflection= 8.33 mm
Load= 84.30 kN

Load Step 13
Deflection= 12.93 mm
Load= 103.33 kN

Load Step 14
Deflection= 14.17 mm
Load= 107.72 kN

Figure 77: Crack propagation at different load steps – FE- BCC
Load Step 2
Deflection= 1.00 mm
Load= 18.97 kN

Load Step 4
Deflection= 2.75 mm
Load= 34.73 kN

Load Step 6
Deflection= 4.85 mm
Load= 55.97 kN

Load Step 9
Deflection= 8.36 mm
Load= 79.89 kN

Load Step 13
Deflection= 96.34 mm
Load= 12.98 kN

Load Step 15
Deflection= 16.18 mm
Load= 108.13 kN

Figure 78: Crack propagation at different load steps – FE-BCB
Chapter 7: Summary and Conclusion

Several techniques are used worldwide to strengthen or repair deteriorated and damaged structures. The use of advanced FRP composite materials has increased during the last three decades to strengthen structural members including slabs, beams, columns, and walls. Hybrid fiber composites, which combine different types of FRP sheets, are thought to be developing momentum in future strengthening projects.

In this study, a hybrid FRP strengthening system was proposed that combines the high strength of CFRP sheets with the high ductility of BFRP sheets, resulting in enhanced composite laminate characteristics. Tensile coupon tests were conducted on different FRP laminates to obtain their mechanical properties, including the ultimate tensile strength, elastic modulus, and elongation at failure values. In addition, a total of ten RC beams with an average concrete compressive strength of 38.78 MPa were cast and tested under four-point bending. Nine beams were strengthened with different combinations of CFRP and BFRP sheets and one beam was used as an un-strengthened control specimen. Afterwards, the general purpose finite element program ANSYS was used to develop eight FE models to numerically simulate the response of the strengthened beams. The FE simulation results were compared with the experimental values. Finally, all results obtained from the experimental testing and FE modeling were used to evaluate the flexural behavior of RC beams strengthened with CFRP and BFRP sheets.

The following observations and conclusions were drawn from this study:

- Coupon tests of different FRP laminates verified that CFRP laminates exhibited higher tensile strength, elastic modulus and lower rupture strain than that of BFRP laminates.
- The hybrid laminate combining CFRP and BFRP sheets (BC) yielded a ductile behavior with enhanced elongation values compared to CFRP laminates, and higher tensile strength values compared to that of BFRP laminates.
- The experimental testing results showed that strengthening RC beams with a hybrid CFRP-BFRP system would provide an improved performance compared to strengthened beams with CFRP or BFRP sheets.
• The proposed hybrid CFRP-BFRP system provided higher flexural capacity and higher stiffness values than that of the un-strengthened control beam specimen.

• The percent increase in the flexural capacity of the strengthened RC beams ranged from 28% to 75% over the un-strengthened beam.

• The percent decrease in the ductility of strengthened RC beams ranged from 50%-88% compared to the un-strengthened beam.

• RC beams strengthened with one and two layers of BFRP laminates failed by FRP rupture, indicating that this FRP strengthening system was fully utilized to its maximum capacity.

• Interchanging the sequence of FRP sheets did not have an impact on the behavior of the strengthened beams. The beams strengthened with CB and BC yielded the same results for strength and ductility. Both beams had an increase in the flexural capacity of 67% compared to the un-strengthened beam. Moreover, both beams had the same reduction in beam ductility (61%) compared to the un-strengthened beam.

• The output from the developed FE model indicated a good correlation between the experimental and FE results at all stages of loading for all modeled specimens. Hence, it was concluded that FE models are valid to predict the response of RC beams strengthened in flexure with an externally bonded hybrid combination of BFRP-CFRP composite sheets.

• The deviation between the experimental and FE results for the load carrying capacity and the associated mid-span deflection values were less than 12%.

• The developed FE model can be used to estimate the ultimate load, mid-span deflection, failure mode, stresses, and strains of RC beams strengthened with different types of hybrid systems.

Further experimental and numerical studies should be carried out to design an optimum hybrid system that can enhance both the strength and ductility of strengthened RC beams in flexure. The developed FE models could be also used for carrying out parametric studies and further investigations to design an optimized hybrid system.
References


Vita

Sahar Samir Choobbor was born in 1988, in Tehran, Iran. She moved with her family to the United Arab Emirates in 1993. She graduated from the National Private School with honors in 2006. After that, she joined the American University of Sharjah for a Bachelor of Science degree in Civil Engineering. During her studies, Ms. Choobbor received the Petrofac Scholarship for distinguished students for two years and graduated cum laude, in Fall 2010.

Ms. Choobbor received an assistantship to pursue a Master of Science degree in Civil Engineering in Spring 2011, from the same university, in which she worked as a Graduate Teaching Assistant.

Moreover, Ms. Choobbor joined Ted Jacob Engineering Group office in Dubai in 2012 and worked as a Structural Engineer for one year. After that, she joined WME consultants, where she works as a Structural Engineer till the present time.