Evaluating the Effectiveness of Bottom-Bonded and Side-Bonded CFRP Sheets of Variable Thickness on the Flexural Capacity of RC Beams

An Undergraduate Thesis

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A dissertation submitted in partial fulfilment of the requirements for the degree of Bachelor of Science in Civil Engineering

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Statement of Approval

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Dedication

To all the unsung pillars, both human and concrete, who silently bear the load until they crack.

This work is dedicated to our parents, whose unwavering support gave us strength; to our teachers, who reinforced our foundation; and to every engineer striving to strengthen the world, one beam at a time.

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This thesis is the result of shared effort, mutual support, and the guidance of those who believed in us every step of the way.

— On behalf of the Thesis Team

Abstract

One of the primary challenges faced by existing structural components, particularly load-bearing beams, is a reduction in flexural capacity arising from outdated design approaches, accumulated damage, and increasing load demands. To address these pressing concerns, modern structural engineering has embraced retrofitting techniques, which integrate advanced materials into existing infrastructures to enhance structural performance and meet contemporary requirements, particularly concerning seismic resistance and structural reliability. Retrofitting involves careful selection of materials such as steel, timber, adhesives, sealants, and fibre-reinforced polymers (FRPs), based on their strength, durability, and adaptability to structural requirements. Among these materials, Carbon Fibre Reinforced Polymer (CFRP) is notably effective due to its lightweight properties, high tensile strength, and resistance to environmental degradation, making it an ideal choice for reinforcing beams without substantially increasing structural weight or compromising aesthetics. While considerable advancements have already been achieved, ongoing research into optimising the flexural performance of RC beams strengthened with CFRP sheets remains essential. Specifically, the effectiveness of bottom-bonded (BB) and side-bonded (SB) CFRP sheets of variable thickness in enhancing the flexural capacity of beams has not been thoroughly explored. This study aims to bridge this gap by analysing three BB and three SB RC beam models retrofitted using CFRP sheets of varying thicknesses through finite element analysis (FEA) in ABAQUS software. Concrete's nonlinear characteristics, including crack initiation and crushing behaviour under load, are modelled using the Concrete Damage Plasticity (CDP) model, while Hashin's failure criteria are employed to evaluate stress distributions and failure modes within CFRP layers. By systematically examining flexural responses such as load-deflection characteristics, crack propagation patterns, and ultimate load-carrying capacities, the research provides valuable insights into the influence of CFRP bonding positions and sheet thickness variability on the flexural behaviour of RC beams. Ultimately, this work contributes toward developing more effective and economical retrofitting solutions, thereby enhancing the structural integrity and extending the lifespan of ageing infrastructure subjected to increasing load demands and potential seismic events.

Keywords: Retrofitting, Carbon Fiber Reinforced Polymer (CFRP), the Concrete Damage Plasticity (CDP), Hashin's failure criteria

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Chapter 01: Introduction

1.1 Overview

Concrete is widely recognised as one of the most important and durable construction materials used in reinforced concrete (RC) structures, primarily due to its excellent fire resistance, long-term durability, and the ability to perform under various environmental conditions. Over the past several decades, RC structures have been constructed at an accelerated rate worldwide, and many of these structures are now ageing. With increasing demands placed on infrastructure and extended service lifespans, deterioration in these structures has become more evident and more critical. This deterioration can occur for a variety of reasons, with natural factors such as high temperatures, excessive humidity, exposure to aggressive chemicals, freeze-thaw cycles, and sustained loading being the most common causes. However, human-induced factors also play a significant role in structural degradation. These include poor design practices, insufficient maintenance routines, changes in loading conditions due to alterations in building use, and unexpected events such as acts of terrorism, accidents, or warfare [1], [2], [3].

Given these challenges, the demolition and replacement of compromised structures is not always a feasible or cost-effective solution. In many cases, this approach demands significant financial investment, long periods of construction downtime, and extensive labour efforts, all of which make it an unattractive option, particularly in urban or critical infrastructure settings. As a result, the structural engineering community has developed several alternative methods aimed at strengthening, retrofitting, and rehabilitating existing structures to restore their load-carrying capacity and extend their operational lifespan. Among these, retrofitting has gained particular attention and is now considered one of the most efficient and practical solutions for enhancing the safety and performance of RC elements such as beams, slabs, columns, and bridge decks [4], [5], [6], [7], [8], [9], [10].

Retrofitting is the process of upgrading existing structures through the application of additional materials or components that enhance performance, durability, and structural safety without necessitating complete reconstruction. These materials can include traditional options like steel plates or more modern composite materials such as Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP), which are widely used today due to their superior properties [11], [12]. In civil engineering, retrofitting is often employed to address structural deficiencies that emerge as buildings age or when they must meet new code requirements or adapt to new functions. The ultimate objectives of retrofitting are twofold: first, to restore or improve the structural capacity of ageing or underperforming elements, and second, to increase the resilience of structures against dynamic and environmental stressors such as earthquakes, strong winds, and increased live or impact loads [13], [14].

One of the most important benefits of retrofitting is its impact on the flexural performance of structural members. In beams, for instance, retrofitting can reduce stress concentrations, improve how loads are distributed along the span, delay the initiation and growth of cracks, and increase the energy absorption capacity of the element under bending stresses [15]. Together, these enhancements allow retrofitted beams to handle greater flexural loads, which in turn increases their long-term reliability and service life. In recent years, composite materials especially CFRP have been increasingly favoured in strengthening applications over traditional materials like steel, primarily due to their high strength-to-weight ratio, resistance to corrosion, and adaptability in a wide range of environmental conditions [16], [17]. CFRP, in particular, has seen widespread use over the past 30 years in strengthening and repairing concrete structures. This material combines high-strength carbon fibres with a polymer resin matrix, typically epoxy, creating a lightweight and extremely strong composite that is both durable and easy to work with on-site. The carbon fibres provide exceptional tensile strength and stiffness, while the polymer resin binds the fibres and transfers stresses between them [18], [19], [20], [21], [22].

Various techniques are available for applying CFRP to RC members, including externally bonded (EB) sheets and near-surface mounted (NSM) strips. Of these, the EB method is particularly popular due to its straightforward application process, reduced labour requirements, and relatively low maintenance demands [23]. External longitudinal CFRP laminates, in particular, have demonstrated promising potential in enhancing both the shear and flexural capacities of RC beams. Just like internal longitudinal steel reinforcement, higher CFRP reinforcement ratios tend to result in greater structural capacity.

One study involving RC cantilever beams retrofitted using externally bonded CFRP sheets secured with mechanical anchorage found that side-bonded specimens significantly improved stiffness before cracking and exhibited better control over crack propagation than other reinforcement configurations. Another study using the side near-surface mounted (SNSM) method showed that varying the number and orientation of CFRP strips could drastically improve flexural performance. Experimental results from that study reported increases of approximately 153% in first-cracking load, 108% in yield load, and 147% in ultimate load, demonstrating how effective properly configured CFRP retrofitting can be [24], [25], [26].

The effectiveness of CFRP strengthening also depends on the specific bonding technique used. When applying CFRP sheets externally to a beam, the method chosen often depends on which surfaces of the beam are accessible be it the bottom, sides, or another area and the specific structural enhancement needed. The two most widely adopted techniques are bottom-bonded (BB) and side-bonded (SB) applications. Traditionally, bottom-bonded sheets are applied to the tension face (the underside) of beams, since this location typically experiences the highest tensile stresses during loading. This method is also favoured for its installation convenience and direct contribution to flexural capacity enhancement [27], [28].

However, practical challenges may arise such as limited surface area, congested geometries, or restricted site access that can complicate bottom installations, especially in double-tee or precast sections. In contrast, side-bonded applications involve adhering CFRP sheets to the vertical faces of the beam. While more labour-intensive due to surface preparation and anchorage requirements, the SB method can improve both shear and flexural performance, especially in scenarios where the bottom face is inaccessible or where added confinement is beneficial. Additionally, side-bonded CFRP laminates are generally less exposed to environmental wear, which can be advantageous in aggressive service environments.

Further research has explored the improvements in flexural capacity achieved through these techniques. Results indicate that beams strengthened with bottom-bonded CFRP sheets can exhibit strength increases ranging from 62% to 92%, while side-bonded configurations can achieve gains between 39.7% and 93.4%. It's important to note, however, that many failure cases involve yielding of internal steel reinforcement before CFRP debonding, which highlights the need for carefully balanced reinforcement design that considers both the internal and external systems for optimal performance [29], [30]. These findings collectively reinforce the value of CFRP retrofitting particularly when optimised through thoughtful configuration and application for extending the life and capacity of RC beams in modern structural systems.

1.2 Scope & Objective

1.2.1 Scope

After analyzing prior studies, we discovered that while considerable research has focused on the general flexural strengthening of beams using externally bonded carbon fiber reinforced polymer (EB-CFRP), there remains a notable gap regarding the influence of CFRP bonding positions and variable thickness configurations on their flexural performance. Unlike uniform CFRP applications, variations in thickness and positioning significantly impact load-carrying capacity, crack formation, stress distribution, and overall structural response. Thus, it is essential to thoroughly investigate how different bonding techniques and thickness variations affect the flexural capacity of reinforced concrete beams. Our study addresses this research gap by evaluating and comparing the flexural performance of reinforced concrete beams strengthened using side-bonded CFRP (SB-CFRP) and bottom-bonded CFRP (BB-CFRP) sheets of variable thickness, employing a detailed three-dimensional finite element model developed in ABAQUS.

1.2.2 Objective

The main objectives regarding this research are pointed out below:

1. To evaluate and compare the flexural performance of RC beams strengthened with BB-CFRP and SB-CFRP configurations under identical conditions.

2. To examine the influence of variable CFRP sheet thickness on the flexural behaviour of these beams.

3. To develop and validate a 3D finite element model that simulates different CFRP bonding configurations and thickness variations.

Chapter 02: Literature Review

This chapter gives a comprehensive thematic review of literature pertinent to this thesis. The review is organised to clearly illustrate existing knowledge gaps and emphasise the uniqueness and specific contributions of our research.

2.1 Flexural Capacity of RC Structures Reinforced with CFRP Sheets

The application of Carbon Fibre Reinforced Polymer (CFRP) for retrofitting RC beams has proven highly effective in enhancing flexural capacity, ductility, and overall structural integrity. Numerous experimental investigations affirm that externally bonded CFRP sheets can significantly boost the flexural performance of RC members by delaying crack initiation, reducing crack propagation, and increasing load-bearing capacity [31], [32].

Among the most commonly adopted techniques, externally bonded (EB) CFRP sheets on the tension face of beams, commonly referred to as bottom-bonded (BB) CFRP, have demonstrated flexural strength gains ranging from 30% to more than 90%, depending on the number of layers, CFRP type, and concrete substrate properties [33]. This configuration is highly effective in resisting tensile stresses and is favoured due to its straightforward application and cost-effectiveness.

One study highlighted that beams retrofitted with BB-CFRP exhibited a 58% increase in ultimate flexural capacity compared to control specimens, alongside improved load-deflection behaviour and reduced mid-span deflections under service loads [34]. The delay in first crack formation was particularly notable, improving both serviceability and durability of the retrofitted member.

Figure 01: Visual representation of RC structure

However, despite these performance benefits, some challenges persist. Premature debonding of the CFRP sheet from the concrete substrate, particularly at the ends or in high-stress regions, can limit the effectiveness of the retrofit. Furthermore, the brittle nature of CFRP may reduce the ductility of the strengthened beam unless the CFRP-to-steel reinforcement ratio is carefully optimised [35], [36].

2.2 CFRP-Based Strengthening Techniques

CFRP strengthening systems can be broadly classified into Externally Bonded (EB), Near-Surface Mounted (NSM), and Side Near-Surface Mounted (SNSM) methods. Each technique has its own set of advantages and limitations, which must be considered during retrofit design.

EB, the most widely used approach, involves bonding CFRP sheets to the external surface of a beam using an epoxy adhesive. It is simple, economical, and effective in enhancing both shear and flexural capacities. However, the primary limitation of this technique is its vulnerability to debonding failure at the CFRP-concrete interface, particularly under cyclic or fatigue loading conditions [37], [38].

Figure 02: Beam with U-shaped CFRP sheet

Figure 03: Beam with Side-bonded CFRP sheet

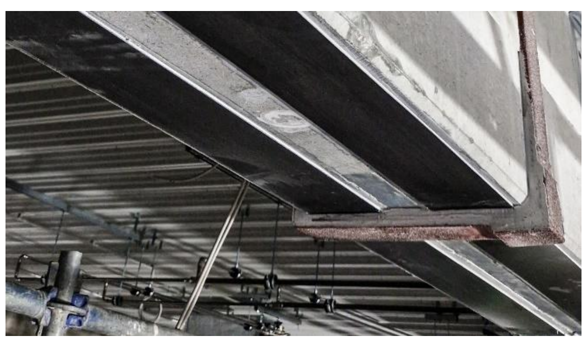

Figure 04: Beam with Side-bonded CFRP sheet

To overcome the weaknesses of EB, the NSM technique was introduced. It involves embedding CFRP rods or strips into grooves cut into the surface of the concrete and filled with adhesive. This method offers superior bond characteristics, reduces exposure to environmental conditions, and significantly enhances load-carrying capacity without affecting aesthetics or clear cover requirements [39].

More recently, the SNSM technique has garnered attention as a hybrid approach. SNSM involves inserting CFRP strips along the sides of beams, which is particularly advantageous when soffit (the underside of a structural element) access is restricted, as in precast or slab-supported beam configurations. This method not only increases flexural strength but also offers enhanced confinement and crack control in both vertical and inclined orientations [40].

Anchorage plays a vital role in all CFRP-based techniques. Studies have shown that rigid anchorage systems in side-bonded configurations significantly reduce debonding failures and promote a more ductile failure mode. Mechanical anchorage, either with end bolts or CFRP wrapping, improves stress transfer efficiency and prolongs the service life of retrofitted elements [41].

2.3 Effects of CFRP Thickness and Bonding Configurations

CFRP thickness and bonding position are critical variables that influence the effectiveness of the retrofit. While most early studies focused on uniform thickness and bottom-bonded applications, recent research has begun to explore how variations in sheet thickness and positioning (bottom, side, or inclined) affect structural performance.

Increasing CFRP thickness or the number of layers generally leads to an increase in flexural capacity, provided the bond between CFRP and concrete remains intact. However, beyond an optimal thickness, additional layers can cause stress concentrations, premature delamination, or reduced ductility due to over-stiffening of the section [42], [43].

Bonding position is equally important. Bottom-bonded (BB) CFRP is most effective at enhancing flexural capacity by directly countering tensile stresses. However, its effectiveness can be limited by geometric constraints, poor surface preparation, or environmental exposure. In contrast, side-bonded (SB) CFRP may be more practical in confined spaces or when soffit access is blocked. Although typically less effective than BB in raising peak flexural strength, SB can contribute significantly to crack width control, stiffness improvement, and load redistribution [44].

One study compared BB and SB configurations with varying thickness and found that SB retrofitting improved first crack load by up to 79% and provided better pre-yield stiffness than BB configurations in certain cases. Additionally, inclined or “U-wrap” configurations showed superior energy dissipation and failure control [45], [46].

Thus, the strategic placement and optimisation of CFRP thickness and orientation, rather than simple maximisation, are critical to ensuring balanced performance without compromising ductility or bond integrity.

2.4 Numerical Modelling for Flexural capacity Prediction

Numerical simulation using Finite Element Modelling (FEM) has emerged as a powerful tool to analyze the structural performance of CFRP-strengthened RC beams. Compared to experimental methods, FEM provides a more economical and scalable means of examining crack initiation, load transfer, stress redistribution, and failure mechanisms. Multiple researchers have developed nonlinear 3D FEM models primarily using software such as ABAQUS to simulate both monotonic and cyclic loading on retrofitted concrete beams with CFRP [47], [48].

In terms of modelling methodology, most studies implement a concrete damage plasticity (CDP) model to represent the nonlinear compressive and tensile behavior of concrete. CFRP is often modelled as a linear elastic orthotropic material, while steel reinforcements are incorporated using embedded element techniques with elastoplastic behavior. The interface between CFRP and concrete is typically simulated using cohesive zone modelling (CZM) or surface-based cohesive contact interactions to capture bond–slip relationships and debonding failures accurately [49].

Mesh sensitivity and element type are critical in these simulations. For concrete, C3D8R (8-node brick elements with reduced integration) is commonly used. For CFRP laminates, S4R shell elements are preferred to ensure computational efficiency while preserving the accuracy of stress transfer. The bonding layer or interface zone is typically defined using zero-thickness cohesive elements (COH3D8) or contact properties that include traction-separation laws.

Several FEM studies calibrated their models using experimental data to achieve high predictive fidelity. One such model accurately replicated load-deflection curves, crack propagation, and ultimate failure loads of bottom- and side-bonded CFRP-strengthened beams with over 95% correlation to laboratory results [49]. FEM has also been used to conduct parametric studies that vary CFRP thickness, bond length, anchorage conditions, and laminate configurations. These studies have demonstrated that even small variations in CFRP layer thickness can influence failure mode transitions from flexural cracking to interface debonding or concrete crushing, especially when anchorage is insufficient [50].

Importantly, FEM allows for simulation under fatigue or cyclic loading, an area where experimental studies are resource-intensive. Progressive stiffness degradation, cyclic crack reopening, and bond fatigue life can be predicted using damage accumulation models embedded into cohesive laws or concrete tensile softening curves. This aspect is particularly critical for infrastructure subjected to repeated vehicular or seismic loads, where fatigue failure may precede static strength loss.

In this context, the FEM methodology employed in this thesis uses ABAQUS to simulate RC beams retrofitted with variable-thickness CFRP laminates in both bottom-bonded and side-bonded configurations. The model incorporates CDP for concrete, elastoplastic steel, cohesive interactions for the CFRP–concrete interface, and stepwise loading to replicate static and potentially cyclic behavior. This approach not only provides validation against existing data but also generates new predictive insights into failure patterns and load-bearing efficiency under different retrofitting scenarios.

2.5 Identified Research Gaps and Thesis Novelty

Although CFRP-based retrofitting of RC beams has been extensively studied, several key research gaps remain:

1. **Limited comparative studies between bonding configurations**: Most research focuses either on bottom-bonded (BB) or side-bonded (SB) CFRP applications in isolation. Very few studies offer a controlled comparative analysis of BB vs. SB performance under similar loading and reinforcement conditions, which is essential for informed design decisions in constrained field scenarios [51].

2. **Neglect of variable CFRP thickness effects**: CFRP thickness is commonly treated as a uniform or secondary parameter. The effects of gradual or differential CFRP thickness on flexural behaviour, crack patterns, and bond integrity are not well understood, especially when applied asymmetrically across beam surfaces [52], [53]. This limits the ability to optimise material use without compromising performance.

3. **Underutilization of FEM for configuration-thickness interaction**: While FEM has been applied to model CFRP-strengthened RC beams, very few studies have used it to jointly evaluate the impact of bonding position and laminate thickness variation. In most cases, FEM validation focuses on uniform BB-CFRP strengthening under monotonic loads, leaving the combined effects of variable geometry and bonding position underexplored [54].

4. **Limited interface modelling in side-bonded systems**: Research often oversimplifies the bond interface, particularly for SB applications where interface shear stress distribution and anchorage performance differ significantly from BB systems. The complexity of side bonding, which includes vertical adhesion and often mechanical anchorage, requires more sophisticated interface modelling techniques and validation.

5. **Insufficient fatigue analysis**: While some FEM studies address the fatigue life of BB-CFRP retrofitting, very few assess fatigue degradation in SB systems or examine how varying CFRP thickness affects cyclic damage accumulation. This leaves a critical gap in design for long-term durability under repeated service loads.

2.5.1 Thesis Novelty

This thesis addresses these gaps by:

1. Comparatively analysing BB-CFRP and SB-CFRP strengthening techniques, under identical geometry, reinforcement, and load conditions, using both numerical modelling and synthesis of existing data.

2. Introducing CFRP thickness variation as a key design parameter and evaluating its influence on flexural behaviour, crack control, and failure mode using a 3D nonlinear FEM model in ABAQUS.

3. Modelling the CFRP–concrete interface with cohesive surface interactions to accurately capture debonding behaviours in both BB and SB configurations.

4. Extending FEM simulations to explore configuration-thickness interactions, offering new insights that are currently unavailable in the literature.

By integrating realistic modelling techniques with targeted comparative analysis, this research not only fills a clear methodological and design gap but also offers practical recommendations for engineers seeking to retrofit RC beams efficiently under site constraints.

2.5.2 Tabular Summary

Table 1: Summary of Selected Literature on CFRP Strengthening of RC Beams

Strengthening Method	CFRP Configuration	Thickness / Layers	Key Findings
EBR	Bottom-bonded	1 layer	58% flexural gain, good ductility[55]
EBR	Side-bonded	1-2 layers	56% deflection ↑, 12% strength ↑[56]
SNSM	Side NSM	2-4 strips	153% crack load ↑, 147% ultimate ↑[57]
EBR with Anchorage	Side-bonded (rigid)	1-2 layers	Improved stiffness, crack control[58]
Inclined EBR	Inclined 45°- 60°	1 layer	Better ductility at 45°-60°[59]
NSM	Bottom NSM	2-3 rods	Good anchorage, reduced failure[60]
SNSM	Side NSM	2-4 strips	Higher energy absorption[61]
SNSM	Horizontal SNSM	3 strips	High crack resistance, flexural ↑[62]
SNSM	Vertical SNSM	4 strips	Vertical strips yield high ductility[63]
Anchored EBR	Side-bonded	Variable	Reduced crack width & slippage[64]
FEM	Side-bonded	N/A	FEM matched 95% with lab results[65]
SB with thickness variation	Side-bonded	0.111 mm x n	79% crack load ↑, brittle mode[66]
SNSM	SNSM	3 strips	Enhanced stiffness, energy dissipation[67]

Chapter 3: Methodology

3.1 Material Properties

3.1.1 Concrete Damage Plasticity (CDP)

Concrete Damage Plasticity (CDP) is a robust constitutive model used to represent the nonlinear, inelastic behavior of concrete under multiaxial loading. It characterizes both tensile cracking and compressive crushing, making it suitable for modeling damage evolution in reinforced concrete elements subjected to flexural loads. In this study, CDP is implemented using ABAQUS to simulate the progressive degradation of RC beams retrofitted with CFRP sheets, accounting for stiffness reduction, plastic strain accumulation, and post-peak softening.

The uniaxial stress-strain relationships in compression and tension are described by the CDP model as shown in Figure 5 and Figure 6, respectively.

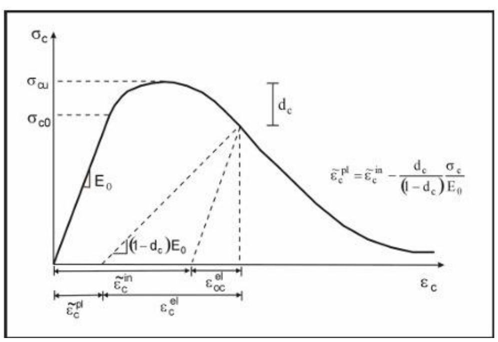

Figure 05: Dependence σ - ε in compression for CDP model

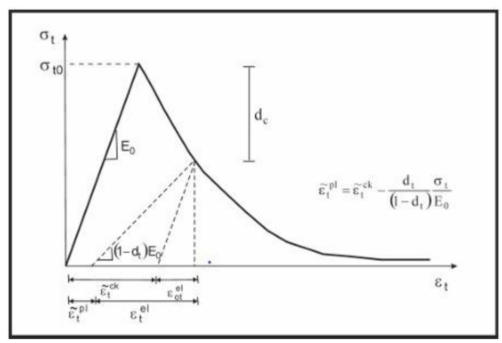

Figure 06: Dependence σ - ε in tension for CDP model

These figures illustrate the decomposition of total strain into elastic and plastic components, incorporating stiffness degradation through scalar damage variables d_c (for compression) and d_t (for tension).

$$\varepsilon_c^{\sim pl} = \varepsilon_c^{\sim in} - \frac{d_c}{1-d_c} \cdot \frac{\sigma_c}{E_0} \quad (1)$$

$$\varepsilon_t^{\sim pl} = \varepsilon_t^{\sim ck} - \frac{d_t}{1-d_t} \cdot \frac{\sigma_t}{E_0} \quad (2)$$

Here,

Table 2: Definition of Symbols Used in Concrete Damage Plasticity (CDP) Formulation

Symbol	Meaning
$\varepsilon_c^{\sim pl}$, $\varepsilon_t^{\sim pl}$	Plastic strain in compression and tension respectively strain not recovered after unloading
ε_c^{in}	Inelastic strain in compression total strain minus elastic part
ε_t^{ck}	Cracking strain in tension strain beyond the elastic limit due to tensile cracking
d_c, d_t	Damage variables in compression and tension scalar values (0 to 1) that reduce stiffness
σ_c, σ_t	Stress in compression and tension respectively
E_0	Initial (undamaged) elastic modulus of concrete slope of initial linear portion of stress-strain curve

To accurately simulate the nonlinear behaviour of concrete in finite element analysis, the Concrete Damage Plasticity (CDP) model parameters must be carefully defined based on material properties and experimental data. The following table summarizes the elastic properties, damage parameters, and inelastic stress–strain relationships used to model concrete class B50 in this study. These parameters were calibrated for both compressive and tensile regimes, including stiffness degradation, hardening behaviour, and damage evolution under loading.

Table 3: The material parameters of CDP model for concrete class B50

Material's parameters	B50	The parameters of CDP model	
		β	38°
Concrete elasticity		m	1
E [GPa]	19.7	$f = f_0 / f^c$	1.12
ν	0.19	γ	0.666
Concrete compression hardening		Concrete compression damage	
Stress [MPa]	Crushing strain [-]	Damage C [-]	Crushing strain [-]
15.0	0.0	0.0	0.0
20.197804	0.0000747307	0.0	0.0000747307
30.000609	0.0000988479	0.0	0.0000988479
40.303781	0.000154123	0.0	0.000154123
50.007692	0.000761538	0.0	0.000761538
40.236090	0.002557559	0.195402	0.002557559
20.236090	0.005675431	0.596382	0.005675431
5.257557	0.011733119	0.894865	0.011733119
Concrete tension stiffening		Concrete tension damage	
Stress [MPa]	Cracking strain [-]	Damage T [-]	Cracking strain [-]
1.99893	0.0	0.0	0.0
2.842	0.00003333	0.0	0.00003333
1.86981	0.000160427	0.406411	0.000160427
0.862723	0.000279763	0.69638	0.000279763
0.226254	0.000684593	0.920389	0.000684593
0.056576	0.00108673	0.980093	0.00108673

3.1.2 Hashin's failure criteria

Hashin’s Failure Criteria is a well-established theoretical approach used to predict the onset of damage in fibre-reinforced composites such as Carbon Fiber Reinforced Polymer (CFRP). It differentiates between various failure modes such as fibre tension, fibre compression, matrix cracking, and matrix crushing based on the type and direction of stress applied. This makes it particularly useful in finite element simulations where realistic modelling of composite failure is critical for assessing structural performance. In this study, Hashin’s criteria were employed to simulate the failure behaviour of CFRP sheets bonded to reinforced concrete beams. To implement this, accurate material input data are essential. The elastic properties of the CFRP lamina, including principal Young’s moduli, Poisson’s ratio, and shear moduli, govern the anisotropic stiffness response under multiaxial loading. Additionally, the unidirectional strength values in tension, compression, and shear serve as key parameters for failure initiation. The following tables present the elastic constants and strength parameters used in the model setup. These values were defined based on manufacturer specifications and literature data to ensure realistic representation of the composite material within the ABAQUS simulation environment.

Table 4: Elastic Properties of CFRP Lamina for Finite Element Modelling

Longitudinal Tensile Strength	**Longitudinal Compressive Strength**	**Transverse Tensile Strength**	**Transverse Compressive Strength**	**Longitudinal Shear Strength**	**Transverse Shear Strength**
2200	2200	61	130	85	40

Table 5: Strength Parameters of CFRP Lamina Used in Hashin’s Failure Criteria

E1	**E2**	**Nu12**	**G12**	**G13**	**G23**
130000	8000	0.28	4500	4500	3600

In the context of progressive failure modelling for composite materials, the damage evolution law governs how material degradation proceeds after failure initiation. For CFRP laminates, fracture energy-based criteria provide a realistic measure of energy dissipation during crack propagation. In this study, a linear softening law was employed with the Energy type selected for damage evolution in ABAQUS. The fracture energy values assigned for both tensile and compressive modes longitudinal and transverse were calibrated to ensure consistency with the laminate's failure behaviour under flexural and shear loading. The following table summarizes the fracture energy parameters used in the simulation model.

Table 6: Fracture Energy Inputs for Damage Evolution in CFRP Lamina (Hashin's Criteria)

Longitudinal Tensile Fracture Energy	**Longitudinal Compressive Fracture Energy**	**Transverse Tensile Fracture Energy**	**Transverse Compressive Fracture Energy**
70	70	0.25	0.25

3.1.3 Reinforcement Properties

In finite element simulations of reinforced concrete structures, accurate definition of reinforcement material properties is critical for ensuring realistic structural response under loading. These properties influence the stiffness, yield behaviour, and plastic deformation of embedded steel elements, which directly affect the accuracy of load distribution, crack propagation, and overall system performance. In this study, three types of steel reinforcement were modelled based on the bar diameters used: 16 mm, 20 mm, and 10 mm tie bars. The following subsections present the elastic and plastic material characteristics assigned to each bar size.

Table 7: Material Properties of 16 mm Reinforcing Bar

Bar – 16 mm	
Property	**Value**
Young's Modulus	200 GPa
Poisson's Ratio	0.3
Yield Stress – Plastic Strain	441 MPa – 0
	615 MPa – 0.1578

Table 8: Material Properties of 20 mm Reinforcing Bar

Bar – 20 mm	
Property	**Value**
Young's Modulus	210 GPa
Poisson's Ratio	0.3
Yield Stress – Plastic Strain	441 MPa – 0
	615 MPa – 0.1578

Table 9: Material Properties of 10 mm Tie Bar

Tie Bar – 10 mm	
Property	**Value**
Young's Modulus	200 GPa
Poisson's Ratio	0.3
Yield Stress – Plastic Strain	453.26 MPa – 0
	613.8 MPa – 0.13771

3.2 Finite Element Analysis (FEA)

3.2.1 Methodology Flowchart

The flowchart presents the structured methodology adopted in this study. It commences with the formulation of the research background and a comprehensive literature review, followed by data collection and model development. The developed model is subjected to both finite element and static analyses to evaluate structural performance. Subsequently, the data is analysed to identify the most suitable bonding configuration and CFRP sheet thickness for rectangular reinforced concrete beams. The process concludes with the formulation of key findings and conclusions.

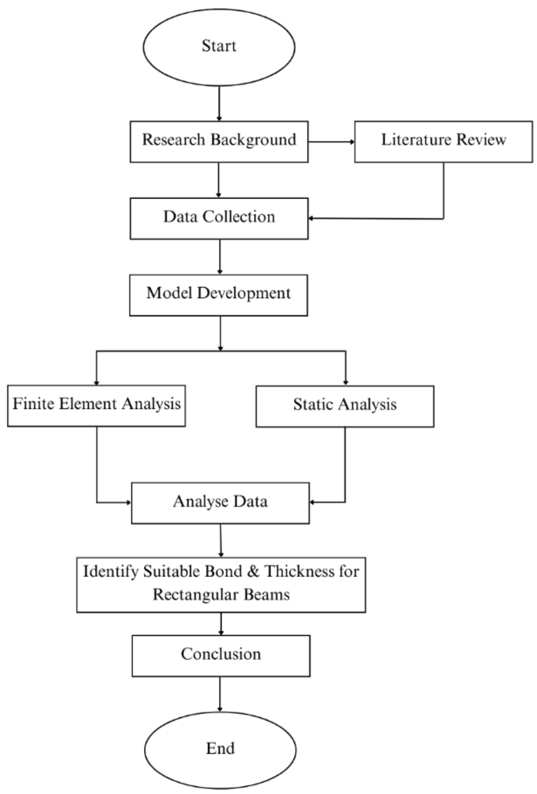

Figure 07: Methodology Flowchart

3.2.2 Application of Boundary Conditions & Loading

In the finite element model, boundary conditions were defined to replicate the experimental three-point bending test configuration accurately. Both beam supports were restrained in all translational degrees of freedom, corresponding to constraints along the X, Y, and Z axes. Mathematically, this is represented as:

$$U_1 = U_2 = U_3 = 0$$

at the support nodes, where U_1, U_2 and U_3 denote displacements in the longitudinal, vertical, and out-of-plane directions, respectively.

The load was applied at the mid-span of the beam using a displacement-controlled approach. A vertical displacement of:

$$U_2 = 10 \text{ mm}$$

was prescribed at the reference point coupled to the rigid loading plate positioned at the center of the span. This method ensures a gradual and uniform application of load, allowing for stable convergence and accurate tracking of nonlinear flexural response.

The loading was applied as a monotonically increasing static displacement, simulating the gradual application of force during physical testing. The analysis continued until the beam exhibited significant flexural deformation or reached its ultimate load-carrying capacity.

3.2.3 ABAQUS Simulation

To analyse the flexural performance of CFRP-strengthened reinforced concrete beams, a detailed finite element model was developed in ABAQUS. The simulation setup included the definition of material properties for concrete, steel reinforcement, and CFRP laminates, as well as the assignment of boundary conditions, interaction properties, and loading protocols that replicate the experimental three-point bending test. The following figures illustrate key stages of the modelling process, including part geometry, mesh discretization, boundary conditions, loading arrangement, and stress distribution during the simulation.

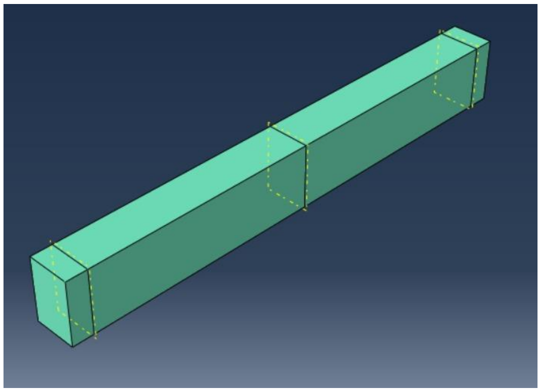

Figure 08: 3D RC beam geometry modelled in ABAQUS

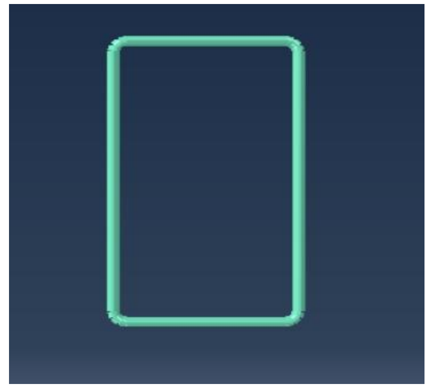

Figure 09: Closed-loop tie bar as transverse reinforcement

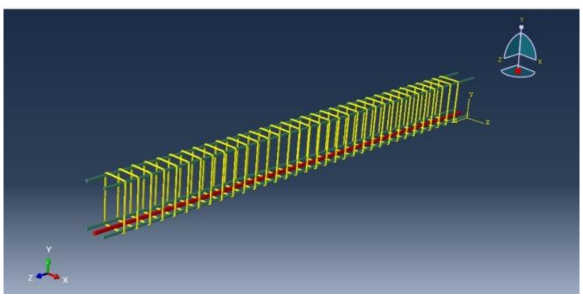

Figure 10: 3D view of embedded longitudinal bars and stirrups

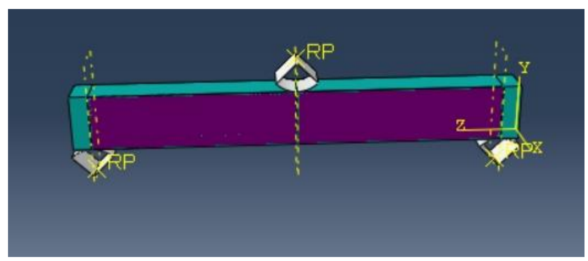

Figure 11: Highlighted supports and loading points in the model

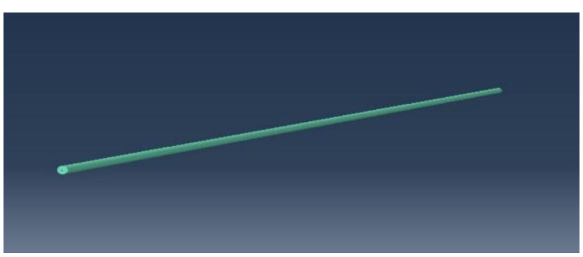

Figure 12: Longitudinal rebar modelled as embedded truss element

Figure 13: Modelled CFRP sheet

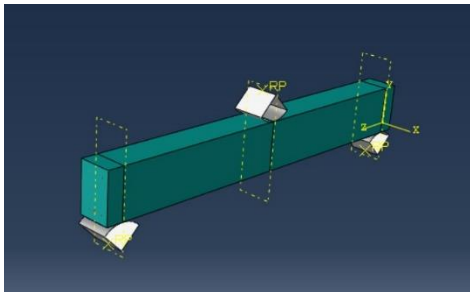

Figure 14: Central loading applied via reference point with constraints

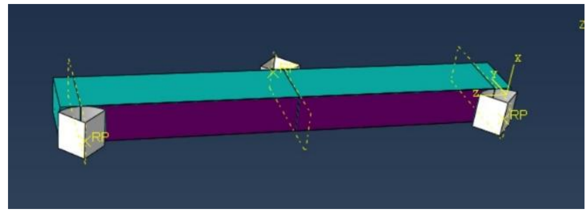

Figure 15: Simply supported beam with load and support references in ABAQUS

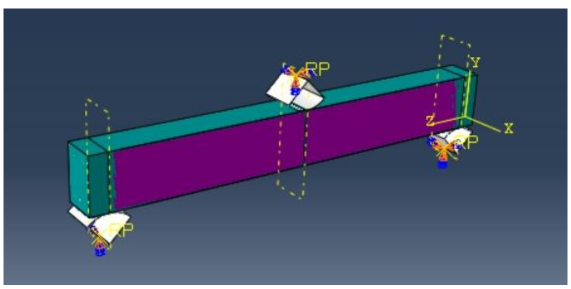

Figure 16: Boundary conditions and loading setup

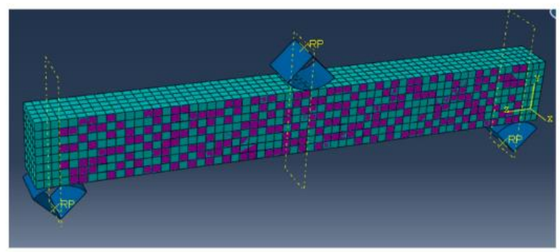

Figure 17: Meshed beam with embedded CFRP and applied boundaries

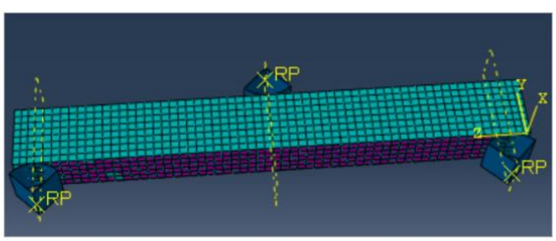

Figure 18: Refined mesh around support and load zones

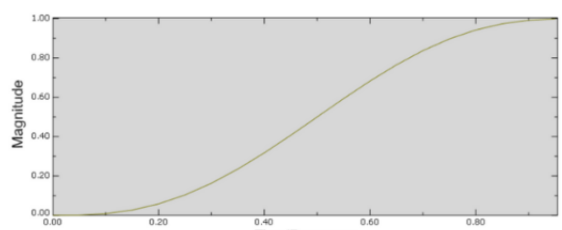

Figure 19: Amplitude curve for static loading

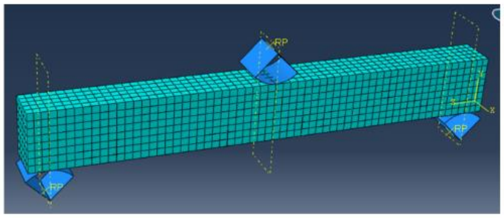

Figure 20: Meshed beam with CFRP layer and boundary conditions

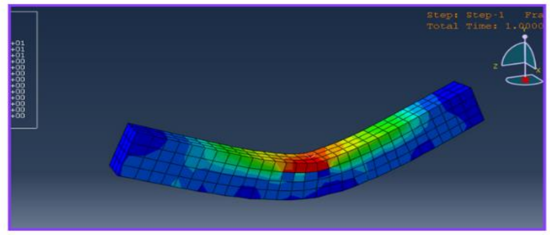

Figure 21: RC Beam without CFRP

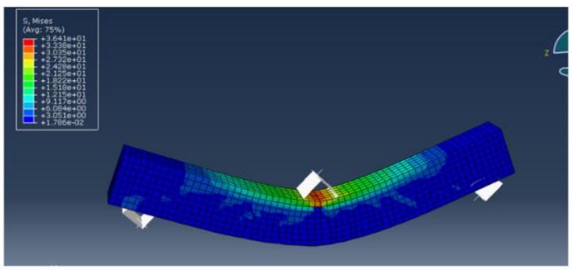

Figure 22: RC Beam with SB CFRP

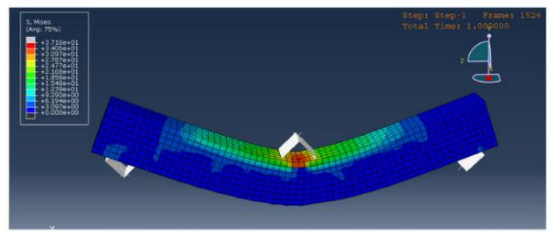

Figure 23: RC Beam with BB CFRP

Chapter 4: Result & Discussion

This chapter presents and discusses the results from finite element analysis (FEA) conducted using ABAQUS to evaluate the flexural performance of reinforced concrete (RC) beams strengthened with bottom-bonded (BB) and side-bonded (SB) CFRP sheets at varying thicknesses of 0.5 mm, 0.75 mm, and 1 mm.

4.1 Effect of Bonding Configuration

The bonding configuration significantly influenced the load-carrying capacity of the CFRP-strengthened beams. Bottom-bonded (BB) CFRP consistently demonstrated superior performance compared to side-bonded (SB) CFRP across all examined thicknesses.

At a deflection of 10 mm:

1. BB-0.5 mm sustained approximately 162,844 N compared to SB-0.5 mm at approximately 115,017 N.

2. BB-1 mm reached approximately 167,295 N, significantly outperforming SB-1 mm at approximately 115,171 N.

Figure 24: Load vs. Deflection Comparison for BB vs. SB (0.5mm)

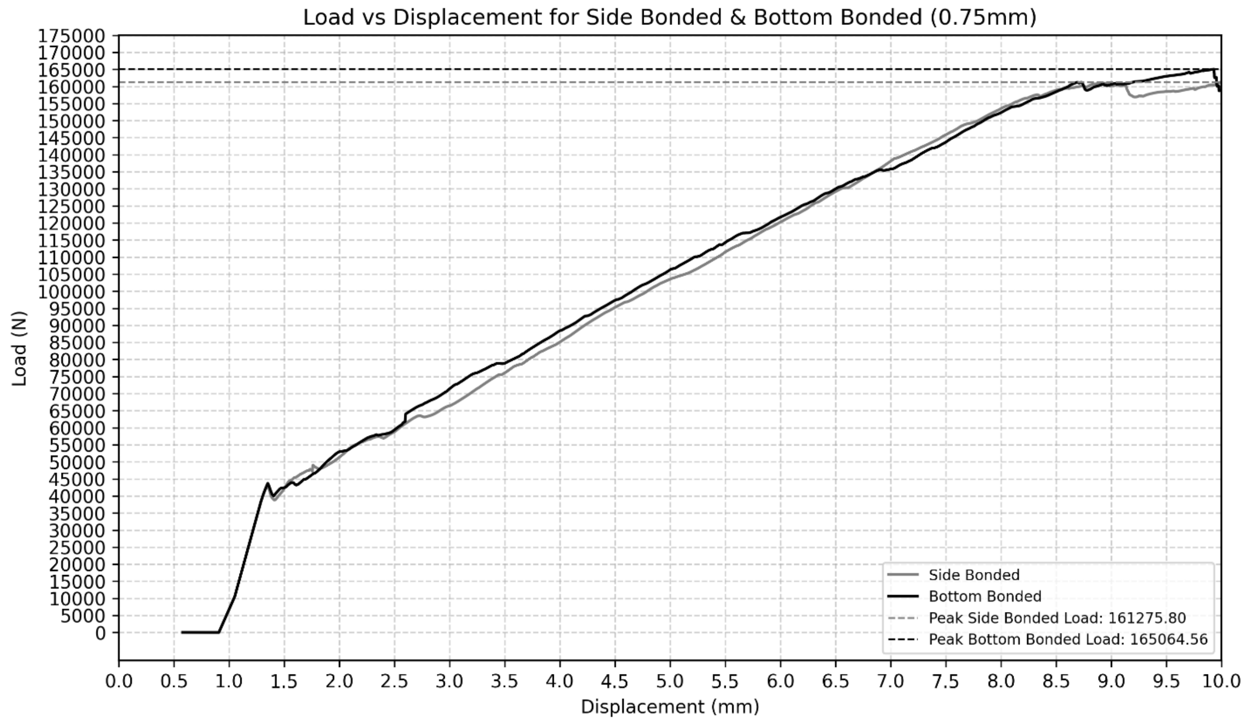

Figure 25: Load vs. Deflection Comparison for BB vs. SB (0.75mm)

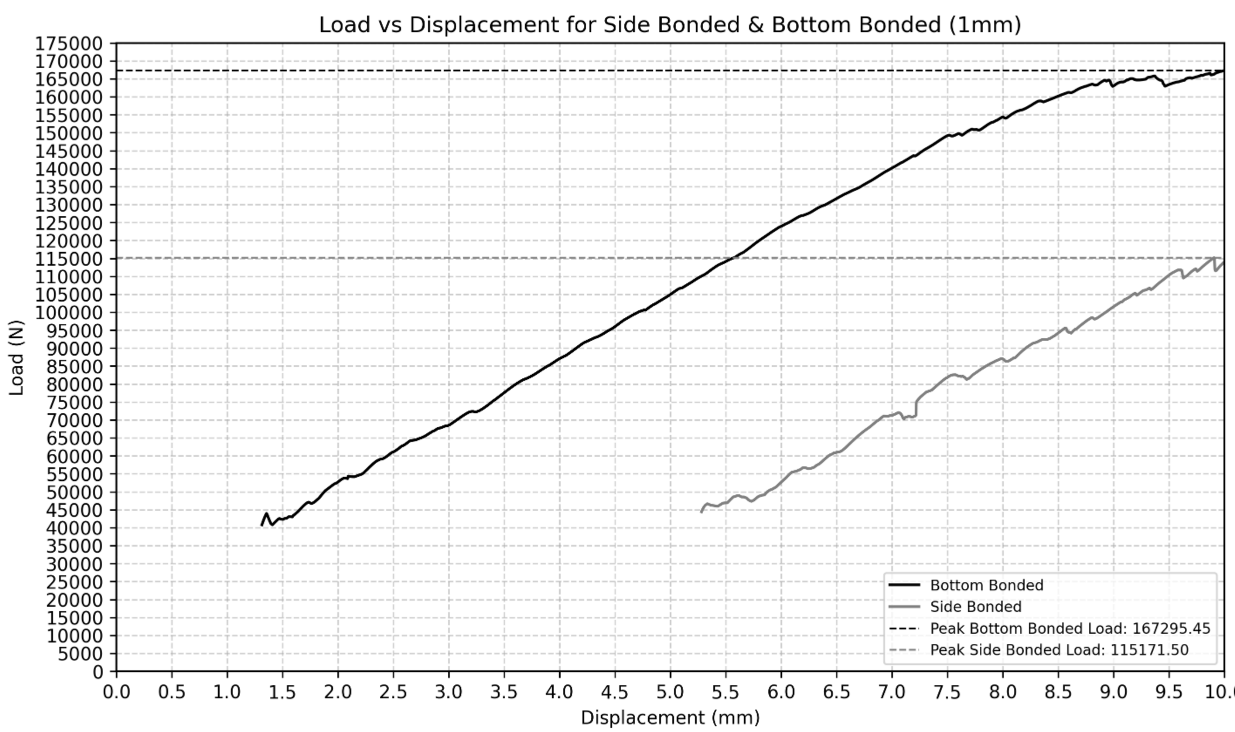

Figure 26: Load vs. Deflection Comparison for BB vs. SB (1mm)

4.2 Impact of CFRP Thickness

The influence of CFRP sheet thickness varied based on the bonding configuration:

Bottom-Bonded (BB):

1. BB-1 mm achieved the highest peak load at approximately 167,295 N.

2. BB-0.5 mm and BB-0.75 mm yielded slightly lower peak loads of approximately 162,844 N and 165,065 N, respectively.

3. Although thicker laminates (1 mm) offered improved stress distribution, they also introduced a higher risk of premature debonding, particularly if adhesive quality was not optimal.

Side-Bonded (SB):

1. SB-0.75 mm exhibited the best performance among side-bonded configurations, with a peak load of approximately 161,276 N.

2. SB-0.5 mm and SB-1 mm demonstrated significantly lower performances, achieving peak loads of approximately 115,017 N and 115,171 N, respectively.

3. SB-1 mm notably underperformed due to increased interfacial stress concentrations leading to premature debonding.

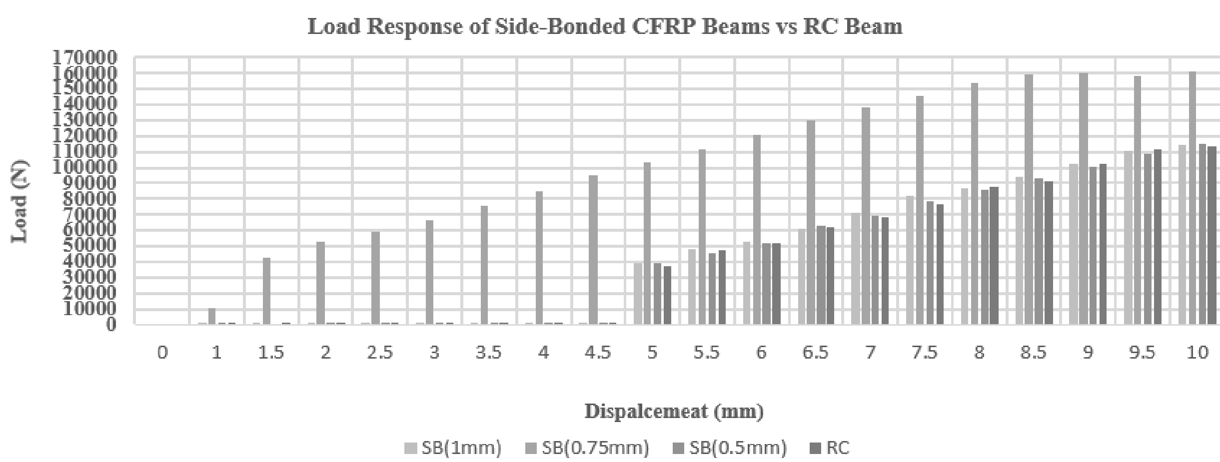

Figure 27: Load Response of Side-Bonded CFRP Beams vs RC Beam

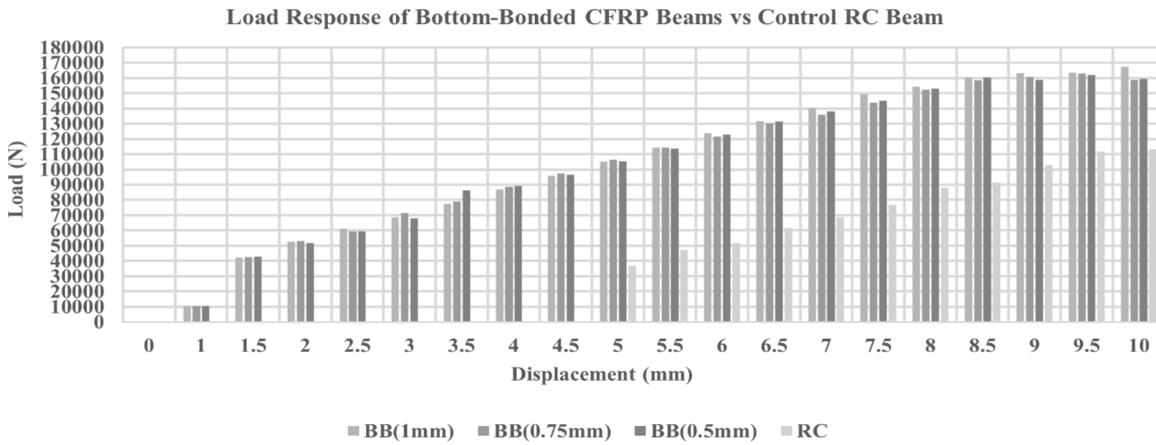

Figure 28: Load Response of Bottom-Bonded CFRP Beams vs Control RC Beam

4.3 Ultimate Flexural Capacity

The ultimate flexural capacity (Mu) for each configuration was calculated using the equation:

Flexural moment (*Mu*) was calculated as,$\text{Mu} = \frac{Pu \, x \, L}{4}$

Table 10 summarizes the ultimate loads and flexural capacities:

Table 10: Ultimate Load and Flexural Capacity of CFRP-Strengthened RC Beams

Specimen	Ultimate Load (N)	Span Length (mm)	Ultimate Flexural Capacity
BB (1 mm)	167295	2798	117022553
BB (0.75 mm)	165065	2798	115462968
BB (0.5 mm)	162844	2798	113908978
SB (1 mm)	115171	2798	80550605
SB (0.75 mm)	161276	2798	112812522
SB (0.5 mm)	115017	2798	80442892
RC	113258	2798	79212871

4.4 Comparative Analysis and Interpretation

The Finite Element Analysis (FEA) clearly demonstrated the benefits of Carbon Fiber Reinforced Polymer (CFRP) strengthening, particularly highlighting the superior performance of bottom-bonded (BB) CFRP. When applied at a thickness of 1 mm, the BB CFRP achieved the highest flexural capacity, increasing the ultimate load resistance by approximately 48% compared to non-retrofitted reinforced concrete (RC) beams, which typically failed at loads around 113,258 N.

Interestingly, the side-bonded (SB) configuration with a thickness of 0.75 mm outperformed the BB configuration at the same thickness. This finding indicates that side-bonded CFRP can achieve notable performance when the laminate thickness is carefully selected, suggesting a thickness-dependent performance efficiency unique to the SB configurations.

In general, bottom-bonded configurations demonstrated effective concrete crushing after steel yielding. Minor debonding was observed at peak loads, particularly for BB CFRP sheets at 1 mm thickness. On the other hand, side-bonded sheets often experienced premature interfacial debonding, significantly affecting their performance, especially at the 1 mm thickness. However, the SB-0.75 mm configuration maintained superior bond integrity, ultimately failing through concrete crushing, much like the BB configurations.

In contrast, the non-retrofitted RC beams consistently displayed brittle shear cracks, underscoring the crucial role of CFRP strengthening in enhancing ductility, improving load distribution, and preventing premature failure.

Chapter 5: Conclusions

This study aimed to address critical gaps in Carbon Fiber Reinforced Polymer (CFRP) retrofitting through rigorous finite element analysis using ABAQUS. The research specifically investigated the effectiveness of bottom-bonded (BB) and side-bonded (SB) CFRP sheets of varying thicknesses on enhancing the flexural capacity of reinforced concrete (RC) beams. Overall, the findings establish significant advancements in understanding CFRP applications, providing valuable strategies for practical implementation in structural engineering.

5.1 Major Findings

The major findings of this study are summarized as follows:

1. Bottom-bonded CFRP with a thickness of 1 mm demonstrated optimal flexural enhancement, achieving a peak load of approximately 167,295 N, approximately 48% higher compared to non-retrofitted beams.

2. Side-bonded CFRP at 0.75 mm thickness proved to be a viable alternative in scenarios where bottom access is impractical, such as bridge girders, reaching a peak load of 161,276 N and closely matching BB system performance.

3. While increasing CFRP laminate thickness generally improved load capacity, side-bonded configurations thicker than 0.75 mm exhibited premature debonding due to interfacial stress concentrations. Conversely, bottom-bonded systems exhibited only minor debonding at ultimate loads.

4. CFRP retrofitting effectively shifted the failure mode from brittle shear cracking, characteristic of non-retrofitted beams failing at approximately 113,258 N, to ductile concrete crushing, significantly enhancing structural resilience.

5. The validated numerical framework incorporating Concrete Damage Plasticity (CDP) for concrete behavior and Hashin’s failure criteria for CFRP damage provided a reliable and cost-effective predictive tool for retrofitted beam behavior.

5.2 Limitations

However, this study faced certain limitations:

1. The effectiveness of CFRP retrofitting significantly depends on the quality of installation, including achieving proper adhesive thickness and uniform bonding, especially for thicker laminates.

2. Ensuring consistent bond quality across surfaces remains a practical challenge during application.

3. Finer mesh sizes used in the simulations improve accuracy but significantly increase computational costs, which may limit broader implementation in resource-constrained settings.

5.3 Future Scope

Future studies should address these challenges by refining both experimental and numerical methodologies. Improved application techniques and reliable bonding methods should be explored to minimize installation inconsistencies. Employing advanced modelling strategies, such as XFEM or adaptive meshing, could optimize simulation accuracy while managing computational demands. Further investigation into alternative material configurations and interfacial treatments could mitigate risks associated with thicker CFRP sheets. The study can also be extended to evaluate the fatigue behavior of CFRP-strengthened RC beams under repetitive or cyclic loading conditions. Performance under both low-cycle and high-cycle fatigue should be assessed to better understand seismic resilience. Life cycle cost and performance evaluations of BB and SB CFRP strengthening techniques should include durability, maintenance frequency, environmental impact, and material sustainability. Laboratory beam tests are recommended to validate numerical findings for real-world applicability.

Reference

[1] R. H. Haddad, R. Al-Rousan, L. Ghanma, and Z. Nimri, 'Modifying CFRP–concrete bond characteristics from pull-out testing', *Mag. Concr. Res.*, vol. 67, no. 13, pp. 707–717, Jul. 2015, doi: 10.1680/macr.14.00271.

[2] R. H. Haddad, N. AL-Mekhlafy, and A. M. Ashteyat, 'Repair of heat-damaged reinforced concrete slabs using fibrous composite materials', *Constr. Build. Mater.*, vol. 25, no. 3, pp. 1213–1221, Mar. 2011, doi: 10.1016/j.conbuildmat.2010.09.033.

[3] R. H. Haddad, M. J. Shannag, and R. J. Hamad, 'Repair of heat-damaged reinforced concrete T-beams using FRC jackets', *Mag. Concr. Res.*, vol. 59, no. 3, pp. 223–231, Apr. 2007, doi: 10.1680/macr.2007.59.3.223.

[4] Q. Wang, T. Li, H. Zhu, W. Su, and X. Hu, 'Bond enhancement for NSM FRP bars in concrete using different anchorage systems', *Constr. Build. Mater.*, vol. 246, p. 118316, Jun. 2020, doi: 10.1016/j.conbuildmat.2020.118316.

[5] S. E. El-Gamal, A. Al-Nuaimi, A. Al-Saidy, and A. Al-Lawati, 'Efficiency of near surface mounted technique using fiber reinforced polymers for the flexural strengthening of RC beams', *Constr. Build. Mater.*, vol. 118, pp. 52–62, Aug. 2016, doi: 10.1016/j.conbuildmat.2016.04.152.

[6] S. V. Grelle and L. H. Sneed, 'Review of Anchorage Systems for Externally Bonded FRP Laminates', *Int. J. Concr. Struct. Mater.*, vol. 7, no. 1, pp. 17–33, Mar. 2013, doi: 10.1007/s40069-013-0029-0.

[7] R. H. Haddad and H. H. Almasaeid, 'Recovering shear capacity of heat-damaged beams using NSM-CFRP strips', *Constr. Build. Mater.*, vol. 105, pp. 448–458, Feb. 2016, doi: 10.1016/j.conbuildmat.2015.12.152.

[8] L. Nguyen-Minh *et al.*, 'Flexural-strengthening efficiency of cfrp sheets for unbonded post-tensioned concrete T-beams', *Eng. Struct.*, vol. 166, pp. 1–15, Jul. 2018, doi: 10.1016/j.engstruct.2018.03.065.

[9] I. A. Sharaky, L. Torres, J. Comas, and C. Barris, 'Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fibre reinforced polymer (FRP) bars', *Compos. Struct.*, vol. 109, pp. 8–22, Mar. 2014, doi: 10.1016/j.compstruct.2013.10.051.

[10] M. Alexander and H. Beushausen, 'Durability, service life prediction, and modelling for reinforced concrete structures – review and critique', *Cem. Concr. Res.*, vol. 122, pp. 17–29, Aug. 2019, doi: 10.1016/j.cemconres.2019.04.018.

[11] M. Ibrahim, T. Wakjira, and U. Ebead, 'Shear strengthening of reinforced concrete deep beams using near-surface mounted hybrid carbon/glass fibre reinforced polymer strips', *Eng. Struct.*, vol. 210, p. 110412, May 2020, doi: 10.1016/j.engstruct.2020.110412.

[12] M. Abdel-Jaber, 'Influence of Externally Bonded CFRP on the Shear Behavior of Strengthened and Rehabilitated Reinforced Concrete T-Beams Containing Shear Stirrups', *Fibers*, vol. 9, no. 12, p. 87, Dec. 2021, doi: 10.3390/fib9120087.

[13] J. Yang, R. Haghani, T. Blanksvärd, and K. Lundgren, 'Experimental study of FRP-strengthened concrete beams with corroded reinforcement', *Constr. Build. Mater.*, vol. 301, p. 124076, Sep. 2021, doi: 10.1016/j.conbuildmat.2021.124076.

[14] S. Aykac, I. Kalkan, B. Aykac, S. Karahan, and S. Kayar, 'Strengthening and Repair of Reinforced Concrete Beams Using External Steel Plates', *J. Struct. Eng.*, vol. 139, no. 6, pp. 929–939, Jun. 2013, doi: 10.1061/(asce)st.1943-541x.0000714.

[15] S. Masoud, K. Soudki, and T. Topper, ‘CFRP-Strengthened and Corroded RC Beams under Monotonic and Fatigue Loads’, *J. Compos. Constr.*, vol. 5, no. 4, pp. 228–236, Nov. 2001, doi: 10.1061/(asce)1090-0268(2001)5:4(228).

[16] G. Xing, O. E. Ozbulut, M. A. Al-Dhabyani, Z. Chang, and S. M. Daghash, ‘Enhancing flexural capacity of RC columns through near surface mounted SMA and CFRP bars’, *J. Compos. Mater.*, vol. 54, no. 29, pp. 4661–4676, Dec. 2020, doi: 10.1177/0021998320937054.

[17] I. Abd El Malik Shehata, L. Da Conceição Domingues Shehata, E. Wagner Freitas Santos, and M. L. De Faria Simões, ‘Strengthening of reinforced concrete beams in flexure by partial jacketing’, *Mater. Struct.*, vol. 42, no. 4, pp. 495–504, May 2009, doi: 10.1617/s11527-008-9397-3.

[18] M. Husain, A. S. Eisa, and M. M. Hegazy, ‘Strengthening of reinforced concrete shear walls with openings using carbon fiber-reinforced polymers’, *Int. J. Adv. Struct. Eng.*, vol. 11, no. 2, pp. 129–150, Jun. 2019, doi: 10.1007/s40091-019-0216-6.

[19] F. Nerilli and G. Vairo, ‘Strengthening of reinforced concrete beams with basalt-based FRP sheets: An analytical assessment’, in *AIP Conference Proceedings*, Rhodes, Greece: Author(s), 2016, p. 270016. doi: 10.1063/1.4952055.

[20] H. Al-Ghanem, A. Al-Asi, M. Abdel-Jaber, and M. Alqam, ‘Shear and Flexural Behavior of Reinforced Concrete Deep Beams Strengthened with CFRP Composites’, *Mod. Appl. Sci.*, vol. 11, no. 10, p. 110, Sep. 2017, doi: 10.5539/mas.v11n10p110.

[21] A. Siddika, Md. A. A. Mamun, W. Ferdous, and R. Alyousef, ‘Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs – A state-of-the-art review’, *Eng. Fail. Anal.*, vol. 111, p. 104480, Apr. 2020, doi: 10.1016/j.engfailanal.2020.104480.

[22] M. M. A. Kadhim, A. H. Adheem, and A. R. Jawdhari, ‘Nonlinear Finite Element Modelling and Parametric Analysis of Shear Strengthening RC T-Beams with NSM CFRP Technique’, *Int. J. Civ. Eng.*, vol. 17, no. 8, pp. 1295–1306, Aug. 2019, doi: 10.1007/s40999-018-0387-8.

[23] H. Zhou, S. S. Zhang, D. Fernando, and T. Huang, ‘The bond-behaviour of CFRP-to-concrete bonded joints under fatigue loading: A damage accumulation model’, *Eng. Fract. Mech.*, vol. 284, p. 109272, May 2023, doi: 10.1016/j.engfracmech.2023.109272.

[24] Md. A. Hosen, M. Z. Jumaat, U. J. Alengaram, and N. H. Ramli Sulong, ‘CFRP strips for enhancing flexural performance of RC beams by SNSM strengthening technique’, *Constr. Build. Mater.*, vol. 165, pp. 28–44, Mar. 2018, doi: 10.1016/j.conbuildmat.2017.12.052.

[25] R. A. Hawileh, W. Nawaz, J. A. Abdalla, and E. I. Saqan, ‘Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams’, *Compos. Struct.*, vol. 122, pp. 468–476, Apr. 2015, doi: 10.1016/j.compstruct.2014.12.010.

[26] Md. A. Hosen, M. Z. Jumaat, U. J. Alengaram, N. H. R. Sulong, and A. B. M. S. Islam, ‘Structural performance of lightweight concrete beams strengthened with side-externally bonded reinforcement (S-EBR) technique using CFRP fabrics’, *Compos. Part B Eng.*, vol. 176, p. 107323, Nov. 2019, doi: 10.1016/j.compositesb.2019.107323.

[27] A. S. D. Salama, R. A. Hawileh, and J. A. Abdalla, ‘Performance of externally strengthened RC beams with side-bonded CFRP sheets’, *Compos. Struct.*, vol. 212, pp. 281–290, Mar. 2019, doi: 10.1016/j.compstruct.2019.01.045.

[28] Y. L. Wang, X. Y. Guo, P. Y. Huang, K. N. Huang, Y. Yang, and Z. B. Chen, ‘Finite element investigation of fatigue performance of CFRP-strengthened beams in hygrothermal

environments', *Compos. Struct.*, vol. 234, p. 111676, Feb. 2020, doi: 10.1016/j.compstruct.2019.111676.

[29] D. Gao, Z. Gu, H. Zhu, and Y. Huang, 'Fatigue behavior assessment for steel fiber reinforced concrete beams through experiment and Fatigue Prediction Model', *Structures*, vol. 27, pp. 1105–1117, Oct. 2020, doi: 10.1016/j.istruc.2020.07.028.

[30] G. Li, Y. Guo, and X. Sun, 'Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates', *Open Civ. Eng. J.*, vol. 6, no. 1, pp. 26–32, Mar. 2012, doi: 10.2174/1874149501206010026.

[31] R. A. Hawileh, W. Nawaz, J. A. Abdalla, and E. I. Saqan, 'Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams', *Compos. Struct.*, vol. 122, pp. 468–476, Apr. 2015, doi: 10.1016/j.compstruct.2014.12.010.

[32] O. R. Abuodeh, J. A. Abdalla, and R. A. Hawileh, 'Prediction of shear strength and behavior of RC beams strengthened with externally bonded FRP sheets using machine learning techniques', *Compos. Struct.*, vol. 234, p. 111698, Feb. 2020, doi: 10.1016/j.compstruct.2019.111698.

[33] B. Hu, Y. Zhou, F. Xing, L. Sui, and M. Luo, 'Experimental and theoretical investigation on the hybrid CFRP-ECC flexural strengthening of RC beams with corroded longitudinal reinforcement', *Eng. Struct.*, vol. 200, p. 109717, Dec. 2019, doi: 10.1016/j.engstruct.2019.109717.

[34] R. Kotynia, H. Abdel Baky, K. W. Neale, and U. A. Ebead, 'Flexural Strengthening of RC Beams with Externally Bonded CFRP Systems: Test Results and 3D Nonlinear FE Analysis', *J. Compos. Constr.*, vol. 12, no. 2, pp. 190–201, Apr. 2008, doi: 10.1061/(asce)1090-0268(2008)12:2(190).

[35] X. J. Chen, X. E. Zhu, and C. H. Gao, 'Comparison and Analysis of RC Beams Strengthened with FRP Bonded on the Side and Bottom Surface', *Adv. Mater. Res.*, vol. 1095, pp. 229–232, Mar. 2015, doi: 10.4028/www.scientific.net/amr.1095.229.

[36] J. Dong, Q. Wang, D. He, and Zhongwei Guan, 'CFRP sheets for flexural strengthening of RC beams', in *2011 International Conference on Multimedia Technology*, Hangzhou, China: IEEE, Jul. 2011, pp. 1000–1003. doi: 10.1109/icmt.2011.6003160.

[37] N. D. D. Nam, H. M. Hung, D. C. Chanh, P. H. Nam, N. M. Hai, and G. Quinci, 'Flexural capacity calculation of RC beams strengthened with prestressed CFRP sheets', *Univ. Danang - J. Sci. Technol.*, pp. 63–69, Nov. 2024, doi: 10.31130/ud-jst.2024.522e.

[38] B. Hu, Y. Zhou, F. Xing, L. Sui, and M. Luo, 'Experimental and theoretical investigation on the hybrid CFRP-ECC flexural strengthening of RC beams with corroded longitudinal reinforcement', *Eng. Struct.*, vol. 200, p. 109717, Dec. 2019, doi: 10.1016/j.engstruct.2019.109717.

[39] H. Ali, J. Assih, and A. Li, 'Flexural capacity of continuous reinforced concrete beams strengthened or repaired by CFRP/GFRP sheets', *Int. J. Adhes. Adhes.*, vol. 104, p. 102759, Jan. 2021, doi: 10.1016/j.ijadhadh.2020.102759.

[40] Md. A. Hosen, M. Z. Jumaat, U. J. Alengaram, N. H. R. Sulong, and A. B. M. S. Islam, 'Structural performance of lightweight concrete beams strengthened with side-externally bonded reinforcement (S-EBR) technique using CFRP fabrics', *Compos. Part B Eng.*, vol. 176, p. 107323, Nov. 2019, doi: 10.1016/j.compositesb.2019.107323.

[41] Z. Lu, J. Li, J. Xie, P. Huang, and L. Xue, 'Durability of flexurally strengthened RC beams with prestressed CFRP sheet under wet–dry cycling in a chloride-containing environment', *Compos. Struct.*, vol. 255, p. 112869, Jan. 2021, doi: 10.1016/j.compstruct.2020.112869.

[42] Y. Murad, ‘An experimental study on flexural strengthening of RC beams using CFRP sheets’, *Int. J. Eng. Technol.*, vol. 7, no. 4, p. 2075, Sep. 2018, doi: 10.14419/ijet.v7i4.16546.
[43] Md. A. Hosen, F. Althoey, M. Z. Jumaat, U. J. Alengaram, and N. H. R. Sulong, ‘Flexural Performance of RC Beams Strengthened with Externally-Side Bonded Reinforcement (E-SBR) Technique Using CFRP Composites’, *Materials*, vol. 14, no. 11, p. 2809, May 2021, doi: 10.3390/ma14112809.
[44] A. Jahami and C. A. Issa, ‘An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams’, *Int. J. Concr. Struct. Mater.*, vol. 18, no. 1, Feb. 2024, doi: 10.1186/s40069-023-00651-y.
[45] M. Emara, A. El-Zohairy, M. Fekry, and M. Husain, ‘Effect of Using ECC Layer on the Flexural Performance of RC Beams Previously Strengthened with EB CFRP Laminates’, *Sustainability*, vol. 14, no. 24, p. 16990, Dec. 2022, doi: 10.3390/su142416990.
[46] A. S. D. Salama, R. A. Hawileh, and J. A. Abdalla, ‘Performance of externally strengthened RC beams with side-bonded CFRP sheets’, *Compos. Struct.*, vol. 212, pp. 281–290, Mar. 2019, doi: 10.1016/j.compstruct.2019.01.045.
[47] Md. A. Hosen, M. Z. Jumaat, U. J. Alengaram, and N. H. Ramli Sulong, ‘CFRP strips for enhancing flexural performance of RC beams by SNSM strengthening technique’, *Constr. Build. Mater.*, vol. 165, pp. 28–44, Mar. 2018, doi: 10.1016/j.conbuildmat.2017.12.052.
[48] G. Li, Y. Guo, and X. Sun, ‘Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates’, *Open Civ. Eng. J.*, vol. 6, no. 1, pp. 26–32, Mar. 2012, doi: 10.2174/1874149501206010026.
[49] G. Li, Y. Guo, and X. Sun, ‘Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates’, *Open Civ. Eng. J.*, vol. 6, no. 1, pp. 26–32, Mar. 2012, doi: 10.2174/1874149501206010026.
[50] Y. Murad, ‘An experimental study on flexural strengthening of RC beams using CFRP sheets’, *Int. J. Eng. Technol.*, vol. 7, no. 4, p. 2075, Sep. 2018, doi: 10.14419/ijet.v7i4.16546.
[51] A. Jahami and C. A. Issa, ‘An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams’, *Int. J. Concr. Struct. Mater.*, vol. 18, no. 1, Feb. 2024, doi: 10.1186/s40069-023-00651-y.
[52] Y. Murad, ‘An experimental study on flexural strengthening of RC beams using CFRP sheets’, *Int. J. Eng. Technol.*, vol. 7, no. 4, p. 2075, Sep. 2018, doi: 10.14419/ijet.v7i4.16546.
[53] A. S. D. Salama, R. A. Hawileh, and J. A. Abdalla, ‘Performance of externally strengthened RC beams with side-bonded CFRP sheets’, *Compos. Struct.*, vol. 212, pp. 281–290, Mar. 2019, doi: 10.1016/j.compstruct.2019.01.045.
[54] G. Li, Y. Guo, and X. Sun, ‘Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates’, *Open Civ. Eng. J.*, vol. 6, no. 1, pp. 26–32, Mar. 2012, doi: 10.2174/1874149501206010026.
[55] R. A. Hawileh, W. Nawaz, J. A. Abdalla, and E. I. Saqan, ‘Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams’, *Compos. Struct.*, vol. 122, pp. 468–476, Apr. 2015, doi: 10.1016/j.compstruct.2014.12.010.
[56] O. R. Abuodeh, J. A. Abdalla, and R. A. Hawileh, ‘Prediction of shear strength and behavior of RC beams strengthened with externally bonded FRP sheets using machine learning techniques’, *Compos. Struct.*, vol. 234, p. 111698, Feb. 2020, doi: 10.1016/j.compstruct.2019.111698.
[57] B. Hu, Y. Zhou, F. Xing, L. Sui, and M. Luo, ‘Experimental and theoretical investigation on the hybrid CFRP-ECC flexural strengthening of RC beams with corroded longitudinal

reinforcement', *Eng. Struct.*, vol. 200, p. 109717, Dec. 2019, doi: 10.1016/j.engstruct.2019.109717.

[58] R. Kotynia, H. Abdel Baky, K. W. Neale, and U. A. Ebead, 'Flexural Strengthening of RC Beams with Externally Bonded CFRP Systems: Test Results and 3D Nonlinear FE Analysis', *J. Compos. Constr.*, vol. 12, no. 2, pp. 190–201, Apr. 2008, doi: 10.1061/(asce)1090-0268(2008)12:2(190).

[59] J. Dong, Q. Wang, D. He, and Zhongwei Guan, 'CFRP sheets for flexural strengthening of RC beams', in *2011 International Conference on Multimedia Technology*, Hangzhou, China: IEEE, Jul. 2011, pp. 1000–1003. doi: 10.1109/icmt.2011.6003160.

[60] X. J. Chen, X. E. Zhu, and C. H. Gao, 'Comparison and Analysis of RC Beams Strengthened with FRP Bonded on the Side and Bottom Surface', *Adv. Mater. Res.*, vol. 1095, pp. 229–232, Mar. 2015, doi: 10.4028/www.scientific.net/amr.1095.229.

[61] H. Ali, J. Assih, and A. Li, 'Flexural capacity of continuous reinforced concrete beams strengthened or repaired by CFRP/GFRP sheets', *Int. J. Adhes. Adhes.*, vol. 104, p. 102759, Jan. 2021, doi: 10.1016/j.ijadhadh.2020.102759.

[62] Z. Lu, J. Li, J. Xie, P. Huang, and L. Xue, 'Durability of flexurally strengthened RC beams with prestressed CFRP sheet under wet–dry cycling in a chloride-containing environment', *Compos. Struct.*, vol. 255, p. 112869, Jan. 2021, doi: 10.1016/j.compstruct.2020.112869.

[63] Y. Murad, 'An experimental study on flexural strengthening of RC beams using CFRP sheets', *Int. J. Eng. Technol.*, vol. 7, no. 4, p. 2075, Sep. 2018, doi: 10.14419/ijet.v7i4.16546.

[64] A. Jahami and C. A. Issa, 'An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams', *Int. J. Concr. Struct. Mater.*, vol. 18, no. 1, Feb. 2024, doi: 10.1186/s40069-023-00651-y.

[65] M. Emara, A. El-Zohairy, M. Fekry, and M. Husain, 'Effect of Using ECC Layer on the Flexural Performance of RC Beams Previously Strengthened with EB CFRP Laminates', *Sustainability*, vol. 14, no. 24, p. 16990, Dec. 2022, doi: 10.3390/su142416990.

[66] G. Li, Y. Guo, and X. Sun, 'Investigation on Flexural Performance of RC Beams Flexurally Strengthened by Side-bonded CFRP Laminates', *Open Civ. Eng. J.*, vol. 6, no. 1, pp. 26–32, Mar. 2012, doi: 10.2174/1874149501206010026.

[67] Md. A. Hosen, M. Z. Jumaat, U. J. Alengaram, and N. H. Ramli Sulong, 'CFRP strips for enhancing flexural performance of RC beams by SNSM strengthening technique', *Constr. Build. Mater.*, vol. 165, pp. 28–44, Mar. 2018, doi: 10.1016/j.conbuildmat.2017.12.052.