Analytical Study on Flexural Behavior of Reinforced Concrete Beams Strengthened with Externally Bonded Carbon Fiber- Reinforced Polymer (CFRP) Laminates

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***Abstract*—This analytical study investigates the flexural behavior of reinforced concrete beams strengthened with externally bonded Carbon Fiber-Reinforced Polymer CFRP laminates. The analysis employs finite element modeling using Abaqus to examine stress-strain relationships, load-bearing capacity, and failure modes of CFRP-strengthened beams versus conventional beams. The study highlights the effectiveness of CFRP reinforcement in improving flexural strength, predicting failure mechanisms, and optimizing design parameters for improved ductility and structural performance.**

***Index Terms*—Abaqus Software, Carbon Fiber-Reinforced Plastic (CFRP), Failure Mechanisms, Finite Element Analysis (FEA), Flexural Strengthening, Load-Displacement Behavior, Reinforced Concrete (RC) Beams, Strengthened Beam Performance.**

I. INTRODUCTION

Reinforced concrete (RC) beams are fundamental structural components widely used in modern infrastructure due to their strength, durability, and ability to carry transverse loads efficiently. However, these beams experience degradation over time due to environmental exposure, increased service loads, and material aging, which can compromise their structural integrity and load-carrying capacity. To address this issue, externally bonded Carbon Fiber-Reinforced Plastic (CFRP) laminates have emerged as an effective strengthening solution, offering high tensile strength, lightweight properties, and excellent resistance to corrosion and environmental factors. By reinforcing RC beams with CFRP, structural performance can be significantly enhanced, ensuring improved flexural strength, extended service life, and greater resistance to cracking and deformation. This study investigates the flexural behavior of CFRP-strengthened RC beams through finite element analysis using Abaqus, examining their load-bearing capacity, failure mechanisms, and overall effectiveness compared to conventional RC beams.

II. LITERATURE REVIEW

1. Maha Assad et al. (2024) - Flexural Strengthening of RC Beams Using CFRP Laminates and Spike Anchors. This study explores the flexural performance of RC beams strengthened with CFRP laminates and secured with CFRP spike anchors. The primary focus is on comparing anchored vs. unanchored CFRP specimens, assessing load-deflection response, failure modes, and strain distribution in CFRP laminates. Results indicate that anchored CFRP laminates significantly enhance flexural capacity, improving resistance to cracking and deformation. The study employs Abaqus software to validate experimental findings, emphasizing the critical role of anchorage systems in optimizing CFRP performance.

2. Thushanthan et al. (2021) - Numerical Analysis of CFRP Strengthened Curved RC Beams. This research conducts finite element analysis (FEA) on six curved RC beams retrofitted with CFRP plates, examining variations in radius of curvature while maintaining identical cross-sections. The study validates numerical models against experimental data, confirming that CFRP effectively increases load-bearing capacity and enhances flexural behavior in curved structures. Findings highlight that larger curvature radii influence displacement behavior, suggesting CFRP

strengthening as a viable solution for bridges and tunnel applications.

3. Jamal A. Abdalla et al. (2020) - Hybrid Strengthening Systems for RC Beams. This study investigates the feasibility of hybrid ductile strengthening systems, combining aluminum alloy (AA) plates, GSM layers, and CFRP laminates to improve RC beam flexural strength. Results reveal that hybrid reinforcements enhance ductility, delaying failure while increasing load-bearing efficiency. The research emphasizes that CFRP alone provides excellent flexural strength, but combining multiple materials creates balanced reinforcement strategies suited for high-strength applications.

III. CARBON FIBER REINFORCED POLYMER

CFRP is a high-performance composite material composed of carbon fibers embedded in a polymer matrix, offering superior strength, lightweight properties, and corrosion resistance. It is widely used in aerospace, automotive, civil engineering, and marine applications due to its high strength-to-weight ratio, fatigue resistance, and thermal stability. CFRP enhances the flexural and shear capacity of RC beams, making it an effective strengthening solution for aging infrastructure. However, challenges such as high manufacturing costs, recycling difficulties, and brittle failure behavior must be considered. Despite these limitations, CFRP remains a valuable material for structural reinforcement, improving load-bearing capacity and extending service life.

CFRP was used as an external reinforcement for RC beams to improve flexural performance. The study utilized finite element analysis (FEA) in Abaqus to simulate the behavior of CFRP-strengthened beams, comparing their load-bearing capacity, failure modes, and deflection trends with conventional beams.

IV. METHODOLOGY

4.1 Literature Review:

A literature review is an essential component of research that involves reviewing and analyzing published literature and research studies relevant to the topic or research question. In this study, previous investigations on the flexural strengthening of RC beams using CFRP laminates were examined. Research studies highlighted CFRP's effectiveness in enhancing load-carrying capacity, ductility, and shear resistance. Various methodologies, including experimental testing, numerical simulations, and finite element modeling, were considered to understand CFRP's impact on structural behavior.

4.2 Modelling:

The first step is to create a detailed three-dimensional geometric model of the structure in Abaqus software. This includes defining RC beams with and without CFRP reinforcement, assigning material properties such as concrete, steel, and CFRP laminates, and applying boundary conditions and loads. The structural model is developed to simulate flexural behavior under applied forces, capturing stress-strain relationships and deformation patterns.

4.3 Analysis & Design:

Finite element analysis (FEA) is conducted using Abaqus to evaluate CFRP reinforcement's influence on beam performance. The analysis involves defining the type of simulation, material interactions, load combinations, and analysis parameters. After setting up the model, buckling analysis, failure mode prediction, and stress-strain evaluations are performed to compare CFRP-strengthened beams with conventional RC beams.

4.4 Results and Discussion:

The Abaqus analysis results provide output data related to beam deformation, load-displacement behavior, stress concentration, and failure mechanisms. The discussion part involves interpreting these results, showing that CFRP reinforcement significantly enhances flexural strength and reduces crack propagation. Comparisons between conventional and CFRP-strengthened beams confirm that CFRP increases load capacity by 53% and improves ductility, proving its effectiveness in structural retrofitting.

V. MODELLING

The model is created in Abaqus to analyze the flexural behavior of a reinforced concrete (RC) beam strengthened with externally bonded Carbon Fiber-Reinforced Plastic (CFRP) laminates. The display units are set to Metric SI, and the design follows standards IS 800:2007 & IS 456:2000. The beam geometry is defined using global coordinates, ensuring accurate positioning for simulation. The specifications of the beam used in this analytical study on flexural behavior of RC beams strengthened with CFRP laminates is given below in the following table.

Beam specifications:

Beam Dimensions	100mm × 200mm × 2100mm
Grade of Concrete	M30
Grade of Steel	Fe500
CFRP Material	High-Strength CFRP Laminates

5.1 Material Assignment

For the beam section, concrete, steel, and CFRP material properties are assigned, including Young's Modulus, Poisson's Ratio, Density, and Yield Stress. The longitudinal reinforcement bars are set with a specific cover thickness.

5.2 Meshing & Boundary Conditions

The beam is meshed into rectangular elements (60mm grid size) to ensure computational accuracy. Boundary conditions replicate real-world constraints, where one end is fixed in X, Y, and Z directions while the other is restricted in X and Y directions. A displacement-controlled load is applied to evaluate beam performance under stress.

5.3 Analysis Setup

Part Creation: The beam is modeled using a solid 3D representation.

Interaction Module: Embedded reinforcement interaction is set between CFRP laminates and concrete to simulate bonding behavior.

Loading Conditions: External loading is applied to examine failure modes and stress-strain distribution.

Finite Element Analysis (FEA): Linear and non-linear buckling analysis are conducted to determine deformation and structural stability.

VI. ANALYSIS

Before analyzing the finite element model, error checks are performed to ensure correct model setup and loading conditions. Any inconsistencies in boundary constraints, material properties, or mesh distribution are identified and corrected before proceeding with the simulation

Prior to running the analysis, load cases are reviewed for optimal performance. Static flexural loading and nonlinear buckling response are prioritized to capture stress-strain behavior. The simulation is initiated, allowing for accurate deformation tracking. The interaction between CFRP and concrete is defined using surface bonding techniques, ensuring proper load transfer. Incremental loading is applied, enabling detailed assessment of displacement, crack propagation, and failure modes in CFRP-strengthened beams.

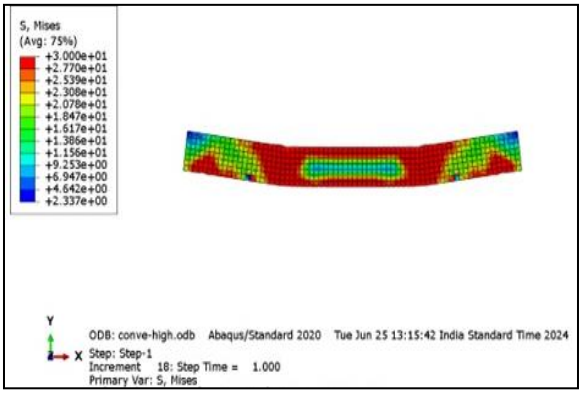

Fig -1: Results of Conventional Beam model

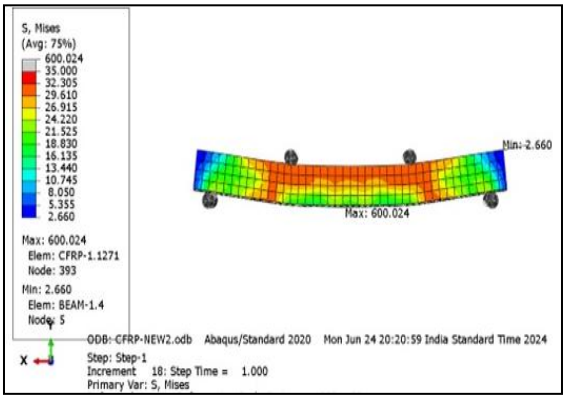

Fig -2: Results of CFRP Beam model

VII. RESULTS AND DISCUSSIONS

This study is carried out to express effect of two different strengthening techniques on flexural behavior of reinforced concrete beam where one strengthened with CFRP and another conventional.

Table 1: Displacement & Force Values of Conventional Beam

Sl. No.	Displacement (mm)	Force (N)
1	0	0
2	0.7	26431
3	1.4	64130
4	2.45	93195
5	4.025	117003
6	6.3875	134101
7	9.9313	145813
8	11.26	150787
9	13.254	152007
10	16.244	153048

11	20.729	153829
12	27.456	154169
13	34.456	153891
14	41.456	153043
15	48.456	151821
16	55.456	150368
17	62.456	148778
18	69.456	147227
19	70	146525

Table 2: Displacement & Force values of CFRP Beam

Sl. No.	Displacement (mm)	Force (N)
1	0	0
2	0.23	102545
3	0.87	123546
4	1.57	135893
5	2.18	150656
6	3.12	173250
7	4.97	186534
8	6.26	198525
9	7.32	204756
10	8.47	213547
11	10.12	225667
12	12.36	235635
13	18.64	239574
14	25.35	226584
15	30.44	218356
16	37.68	215321
17	45.62	203325
18	55.61	196305
19	70	207808

- The CFRP beam shows 53% higher load carrying capacity than the conventional beam.
- Reinforced concrete beam without any strengthening exhibits typical flexural behavior.
- Strengthened models exhibited shear failure, yet flexural moment capacity and flexural strength of the beams are increased.
- The models strengthened with CFRP sheets exhibited better behavior regarding both for flexural strength and flexural performance.
- When compared to the conventional beam, the slope of both stages of the curve raised significantly and marginally for beams with CFRP sheets.
- The findings show that an increment in length, layer number, and width of the CFRP sheet enhances load and deflection capacity once the primary flexural fracture is formed.
- Also, the results cleared that the adding of CFRP sheets improved the ultimate strength and ultimate deflection.

The Load Vs Displacement comparison graph for the conventional beam and Carbon Fiber Reinforced Polymer (CFRP) Laminated beam is shown in the figure 3. It shows that the beam laminated with CFRP sheet shows good results in comparison with the conventional beam. CFRP beams also enhances the beam performance thus improving the flexural strength and ductility.

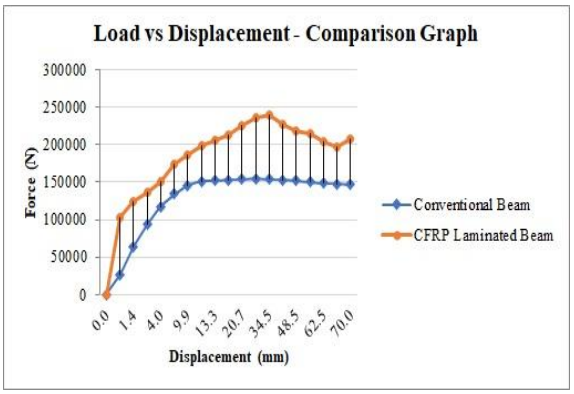

Fig -3: Results of Conventional & CFRP Beam model

VIII. CONCLUSIONS

The main objective of this study is to analyze the flexural behavior of RC beams strengthened with externally bonded CFRP laminates. Parameters such as load-bearing capacity, failure modes, load-displacement behavior, and stress distribution are examined, leading to the following conclusions:

1. CFRP reinforcement significantly enhances beam performance, improving flexural strength and ductility.
2. Externally bonded CFRP laminates increase load-carrying capacity, reducing deformation and enhancing stiffness.
3. CFRP prevents excessive deflection, minimizing structural damage and delaying failure.
4. Strengthening with CFRP improves crack control, ensuring better long-term structural performance.

5. Layer configuration plays a vital role, with multiple CFRP layers optimizing strength and durability.
6. Anchorage techniques enhance CFRP efficiency, improving load transfer and reinforcement bonding.
7. Numerical simulation results align with experimental studies, validating CFRP's effectiveness as a retrofitting solution.

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