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Behaviour Of Externally Bonded Steel I-Section with Fiber Reinforced Polymer Under Effect of Bending

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***Abstract*—Fiber Reinforced Polymer (FRP) sheets, particularly those reinforced with Carbon Fiber (CFRP) and Basalt Fiber (BFRP), have emerged as effective materials for strengthening and rehabilitating steel structures. This study evaluates the flexural performance of rolled steel I-beams reinforced with CFRP and BFRP strips. FRP materials offer significant advantages including high tensile strength, corrosion resistance, and adaptability to irregular surfaces where conventional steel plates are less practical. CFRP is recognized for its superior tensile strength and fatigue resistance, while BFRP provides a cost-effective alternative with commendable mechanical and chemical properties. A finite element model was developed using ANSYS software to simulate the behavior of reinforced I-beams under flexural loading, with results validated experimentally. The findings highlight the comparative effectiveness of CFRP and BFRP in structural strengthening, emphasizing the balance between performance and economic feasibility. This research supports the wider application of FRP reinforcement as a durable, efficient, and sustainable solution for enhancing the service life and performance of steel structural components.**

1. INTRODUCTION

1.1 GENERAL:

Fiber Reinforced Polymer (FRP) sheets have been predominantly applied to enhance the strength and performance of concrete and steel structural components. Over the years, many researchers have explored this method extensively. FRP materials offer notable advantages, particularly in resisting corrosion and chemical deterioration. One key benefit of FRP sheets is their flexibility, allowing them to be used on curved or irregular surfaces—an area where steel plates often fall short due to welding difficulties. These sheets are produced by embedding continuous fibers into a polymer-based resin matrix, which helps unify and reinforce the structure. In civil engineering applications, carbon and basalt fibers are the most frequently used. This study specifically focuses on the evaluation of Basalt Fiber Reinforced Polymer (BFRP) and Carbon Fiber Reinforced Polymer (CFRP) strips.s

The advantages of FRP in structural applications stem from its high tensile strength, resistance to corrosion, and long service life. It can effectively restore compromised structural elements. FRP reinforcement is also beneficial for steel structures by extending fatigue life and reducing crack development—provided that galvanic corrosion is avoided and proper bonding is ensured. Currently, the use of FRP materials, particularly carbon and basalt fibers, is gaining momentum in strengthening applications due to their efficiency and potential. BFRP is particularly attractive for its low cost and widespread availability, in addition to favorable chemical and mechanical performance. On the other hand, CFRP is primarily employed in addressing fatigue-related damage.

This study aims to investigate the flexural performance of rolled steel I-beams with suitable cross-sections. A simulation model was created to evaluate the behavior of these I-beams reinforced with BFRP and CFRP strips, and the findings were compared with experimental results using ANSYS software. FRP sheets are now recognized as an effective method for enhancing both concrete and steel structures, especially in cases involving strength degradation, fatigue damage, or crack formation. Their durability and exceptional resistance to environmental damage make them an ideal solution for long-term structural rehabilitation.

Unlike conventional strengthening techniques such as steel plate bolting, Fiber Reinforced Polymer (FRP) sheets offer greater adaptability due to their flexibility. They can be applied in areas where attaching steel plates through welding or bolting is not feasible, especially on curved, uneven, or irregular surfaces. FRP sheets are composed of continuous fibers embedded in a polymer resin matrix, which facilitates load transfer among the fibers and ensures structural integrity. This combination results in a high strength-to-weight ratio and improved resistance to environmental degradation. Carbon Fiber Reinforced Polymer (CFRP) and Basalt Fiber Reinforced Polymer (BFRP) are widely adopted in civil engineering for their excellent mechanical properties and application-specific advantages.

This study is aimed at examining the structural performance of steel I-beams reinforced with CFRP and BFRP sheets. These two materials were chosen based on their distinct characteristics:

- CFRP: Noted for its outstanding tensile strength and effectiveness in mitigating fatigue damage in steel members. When properly bonded and galvanic corrosion is prevented, CFRP significantly extends the fatigue life of structures.
- BFRP: A more economical alternative to CFRP, BFRP offers commendable chemical and mechanical properties and is especially advantageous in cost-sensitive projects.

FRP sheets are a practical solution for restoring the structural capacity of deteriorated elements and increasing their service life. When applied to steel beams, they enhance load-bearing ability, control crack development, and improve flexural behavior, thereby ensuring greater long-term performance. The use of FRP in structural strengthening is expanding across industries due to its advantages in strength enhancement, corrosion resistance, and economic viability.

The objective of the present research is to assess the flexural response of rolled steel I-beams with suitable cross-sections, strengthened using CFRP and BFRP sheets. A finite element analysis model was created using ANSYS software to simulate the flexural behavior under loading conditions. The simulation outcomes were validated through experimental testing to confirm their accuracy.

This study provides insights into the comparative effectiveness of CFRP and BFRP in structural reinforcement. It also highlights the economic feasibility of using BFRP in scenarios with financial constraints, while emphasizing the superior performance of CFRP in high-demand applications. The findings aim to contribute to the advancement of FRP-based reinforcement technologies and promote their wider application in structural engineering.

2. METHODOLOGY

The proposed research follows a systematic and multi-disciplinary approach to evaluate the structural behavior of FRP-strengthened steel I-sections under various types of loading, i.e., pure bending, pure torsion, and combined bending-torsion. The methodology follows a four comprehensive stepwise approach:

2.1 MATERIAL CHARACTERIZATION:

This initial stage focuses on the mechanical characterization of the constituent materials, which is critical for both the numerical modelling and experimental analysis phases. The accuracy of any simulation or physical prediction relies heavily on the quality and precision of the input material properties.

Objective:

To establish the important mechanical and physical properties of steel sections exposed bare (CFRP and BFRP) through standardized laboratory testing.

Detailed Procedure:

A) Sample Preparation

Specimens were precisely prepared using mild steel I-sections along with CFRP and BFRP strips, following standard ISO guidelines to maintain uniformity. The steel surfaces were cleaned and mechanically treated to ensure a consistent bonding profile for the FRP application. FRP strips were cut and arranged with controlled fiber orientation to maintain uniform structural behavior during testing.

B) Steel Material Testing

Mechanical evaluation of the steel included tensile testing to determine essential properties such as Young’s modulus, yield strength, ultimate tensile strength, and elongation capacity. Hardness assessment was carried out using Brinell or Rockwell methods to understand surface behavior influencing adhesive bonding. When necessary, Charpy impact testing was done to evaluate the material’s toughness under dynamic or low-temperature conditions. Poisson’s ratio was determined by measuring the strain in both longitudinal and transverse directions during loading.

C) FRP Material Testing

CFRP and BFRP strips were subjected to tensile tests to measure their strength characteristics, strain limits, and stiffness. Interlaminar shear strength was assessed to understand their resistance to internal sliding between layers. A modified pull-off test was used to determine the adhesion quality between the FRP and steel surfaces when bonded with epoxy resin. Where applicable, resistance to thermal stress and chemical exposure was evaluated to simulate real-life durability in aggressive environments.

D) Documentation and Data Analysis

All test results were thoroughly recorded and organized into structured datasets. Statistical methods were applied to assess the reliability and variation within the results. The material properties obtained from testing were used as critical inputs in the ANSYS simulation model to replicate the physical behavior under applied loading. These simulation results were then cross-verified with experimental findings to confirm their accuracy and validate the reinforcement effectiveness of the FRP materials.

2.2 DEVELOPMENT OF ANALYTICAL MODEL:

This phase seeks to emulate actual FRP-strengthened I-beam behaviour by Finite Element Analysis (FEA) with ANSYS Workbench or equivalent software. An elaborate FEM model enables predictions of load-deformation characteristics, stress distribution, and possible failure mechanisms.

Objective:

To create and tune a finite element model capable of precisely simulating the behavior of steel I-beams reinforced with CFRP and BFRP under bending, torsion, and combined loading.

Detailed Procedure:

A) Geometry Modelling

A detailed 3D model of the rolled steel I-beam was developed using CAD tools, based on actual physical dimensions including web height, flange width, thickness, and total length. The FRP reinforcement was represented as thin composite layers, externally bonded to the flanges or web surfaces, following the configurations used in the experimental phase of the study.

B) Material Definition

Material properties for each component—steel, CFRP, and BFRP—were defined using the values obtained from experimental characterization. The FRP strips were modeled as orthotropic materials to correctly simulate their anisotropic behavior, ensuring accurate representation of their directional stiffness and strength.

C) FRP-Steel Interface Modelling

The interface between the FRP strips and the steel surface was simulated using contact elements that mimic adhesive bonding behavior. Where necessary, bond-slip relationships or cohesive zone models were introduced to simulate potential delamination or debonding effects under loading, enhancing the model's realism in predicting failure modes.

D) Boundary Conditions and Loading

Structural constraints were applied to simulate actual support conditions, such as simply supported or cantilever setups. Loading scenarios were applied to represent different types of stress environments, including pure bending through central or dual-point loads, pure torsion via end-applied torques, and combined bending-torsion conditions to evaluate multi-axial behavior.

E) Meshing and Convergence Study

A computational mesh was generated using either tetrahedral or hexahedral elements, refined in critical regions for better resolution of stress and strain gradients. A mesh convergence study was performed to ensure that the simulation results remained consistent while optimizing computational time and resource usage.

F) Simulation and Data Extraction

Finite element simulations were executed under both static and nonlinear conditions to capture the full range of structural behavior. Output data such as stress contours, strain fields, deflection patterns, and potential failure locations were extracted and analyzed to assess the effectiveness of the FRP reinforcements and to validate results against experimental outcomes.

G) 2.3 EXPERIMENTAL TESTING:

This phase provides real-world validation of the numerical model by conducting full-scale laboratory tests on fabricated specimens.

H) Objective:

To physically investigate the flexural and torsional response of bare and FRP-strengthened steel I-beams, and compare the observed behaviour with numerical predictions.

Detailed Procedure:

A) Specimen Fabrication

Steel I-sections were manufactured to specified dimensions as per the experimental design. The surfaces intended for FRP application were meticulously prepared through grinding and sandblasting to enhance adhesion quality. CFRP and BFRP strips were then bonded onto the steel sections using high-performance epoxy adhesives, applied under carefully controlled environmental conditions including temperature, pressure, and curing duration to ensure optimal bonding strength.

B) Test Setup

The prepared specimens were installed onto a universal testing machine (UTM) or a specially designed test rig. For bending tests, either three-point or four-point loading methods were employed to simulate flexural stress. Torsional behavior was examined by applying torque via rotary actuators or custom torsion arms designed for this purpose. In cases requiring simultaneous loading, a hybrid test configuration was used to impose both bending moments and torsional forces on the specimens concurrently.

C) Instrumentation

Strain gauges were strategically affixed to critical locations on the specimens, including the top flange, web, and on the surface of the FRP layers, to accurately capture local strain variations during loading. Linear Variable Differential Transformers (LVDTs) or displacement transducers were installed to measure vertical deflections. Data acquisition systems with high sampling rates were employed to record load, displacement, and stress-strain responses in real time, ensuring detailed monitoring of the specimen behavior.

D) Failure Observation and Post-Test Analysis

Throughout testing, visual and instrumental observation documented the onset and propagation of cracks, debonding of FRP sheets, buckling phenomena, and yielding in the steel components. The mode and precise location of failure were recorded for each specimen. Comparative analysis was then conducted to evaluate the relative effectiveness of CFRP and BFRP reinforcements in enhancing the load-carrying capacity and delaying failure under various loading conditions.

2.4 VALIDATION OF ANALYTICAL MODEL:

This stage ensures the credibility of the numerical model by comparing simulated results with experimental findings. A strong correlation between the two confirms the model's reliability for real-world application.

Objective:

To verify and calibrate the analytical model developed in ANSYS by comparing its results with experimental data, ensuring high fidelity and predictive accuracy.

Detailed Procedure:

A) Result Comparison

Key parameters were analyzed to evaluate performance, including maximum load-bearing capacity, peak deflections, strain measurements at designated points, and the initiation and precise location of failure within the specimens.

B) Error Quantification

The differences between numerical simulation outcomes and experimental results were quantified by calculating the percentage deviations. Statistical tools such as Root Mean Square Error (RMSE) and correlation coefficients were employed to assess the accuracy and reliability of the analytical model.

C) Model Refinement

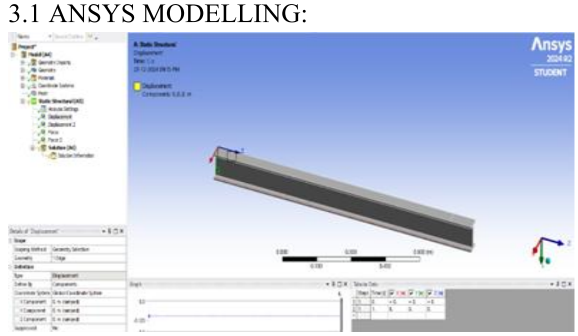
Where significant variations were identified, model parameters were refined accordingly. This included adjustments to boundary conditions, material interface characteristics, and mesh density. Additionally, the model was enhanced by incorporating realistic factors like residual stresses, adhesive degradation, or other secondary effects to improve fidelity.

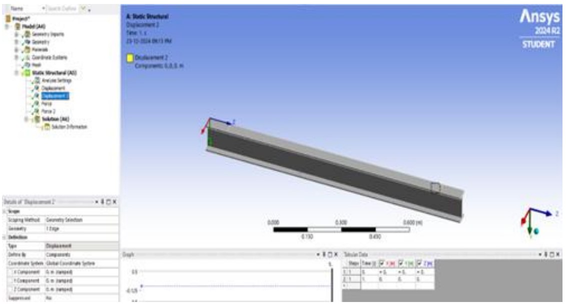
D) Final Validation

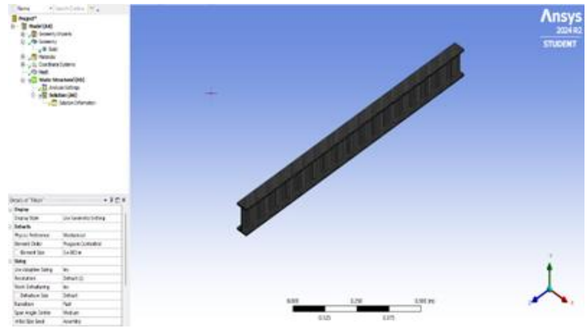
Simulations were repeated using the updated parameters to verify improvements. Upon achieving close agreement with experimental data, the model was established as a dependable framework for predicting the structural response of FRP-strengthened steel I-beams under complex loading scenarios.

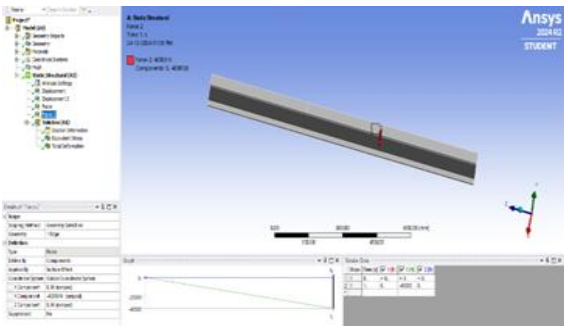
3._TESTING AND MODELING

3.1 ANSYS MODELLING:

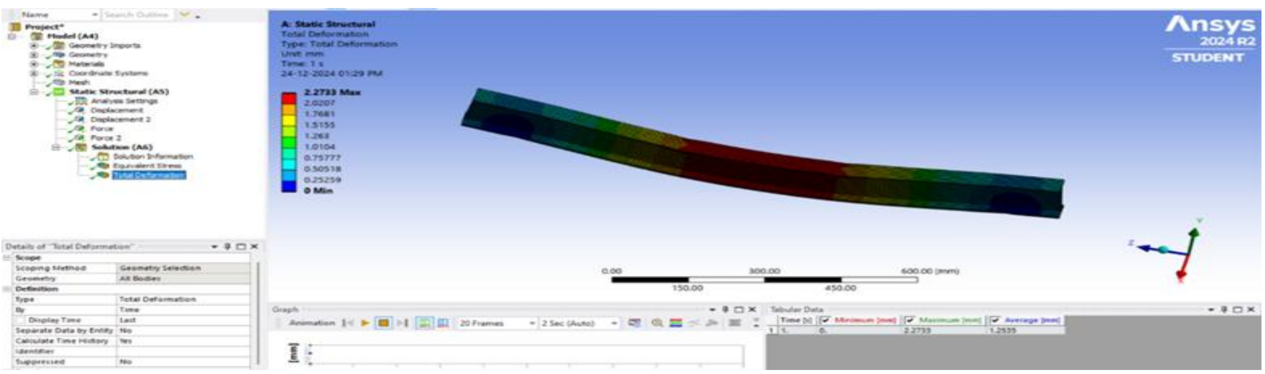




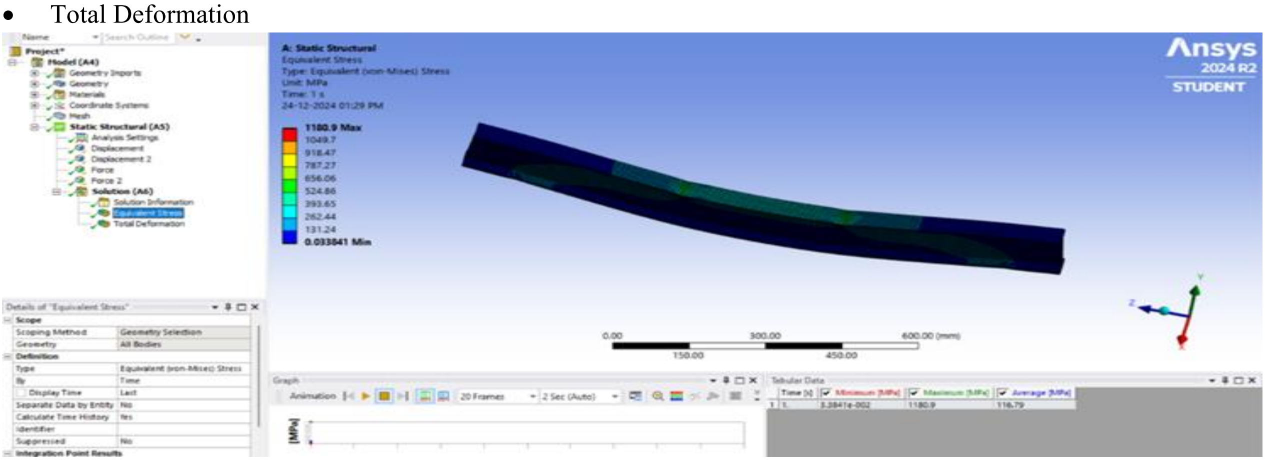




- Result

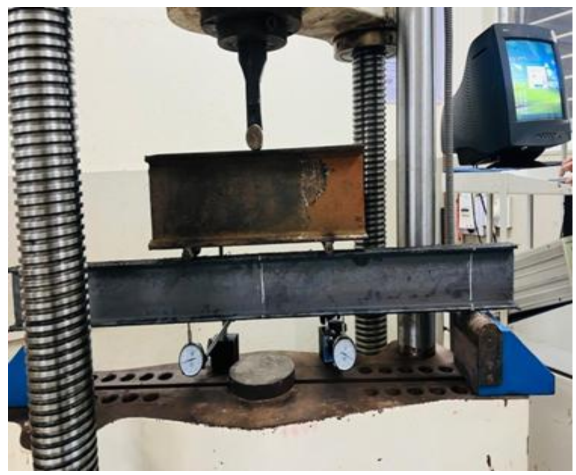


- Total Deformation

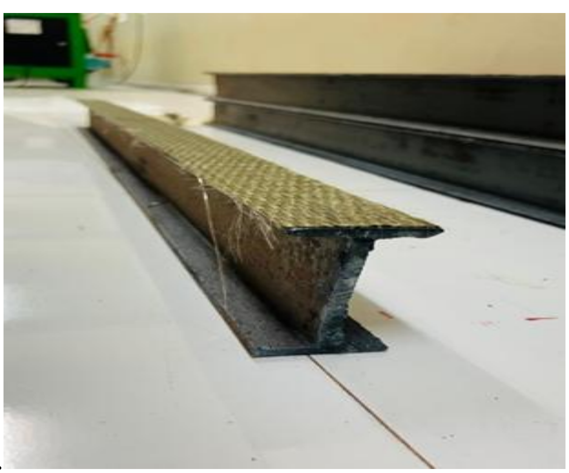


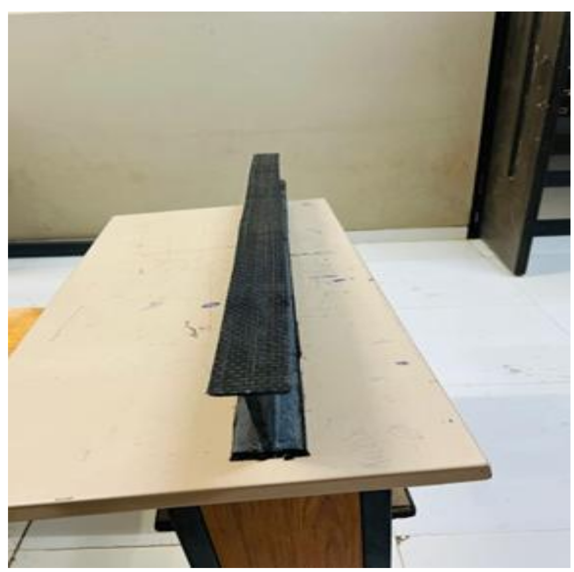
TESTING OF CONTROL BEAM

TESTING OF CONTROL BEAM With CFRP

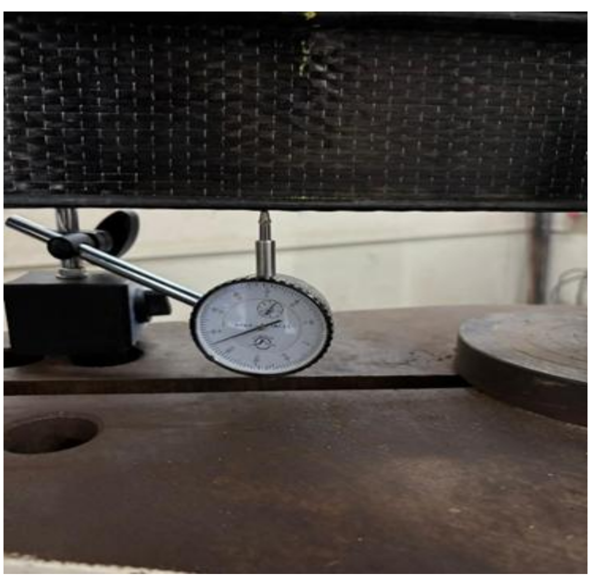


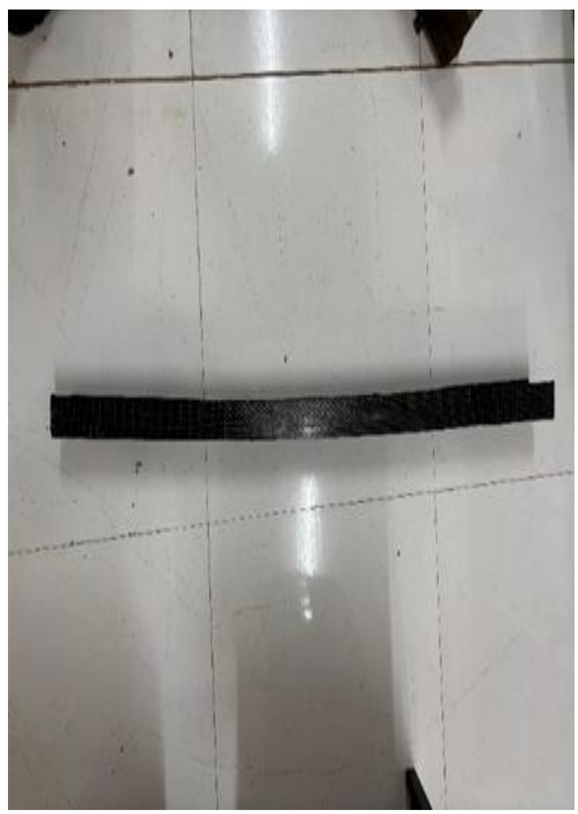
TESTING OF CONTROL BEAM With BFRP



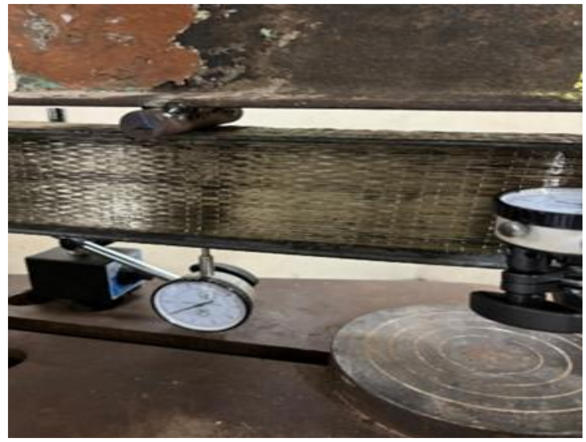


TESTING OF CONTROL BEAM WITH ALL WRAPPED CFRP



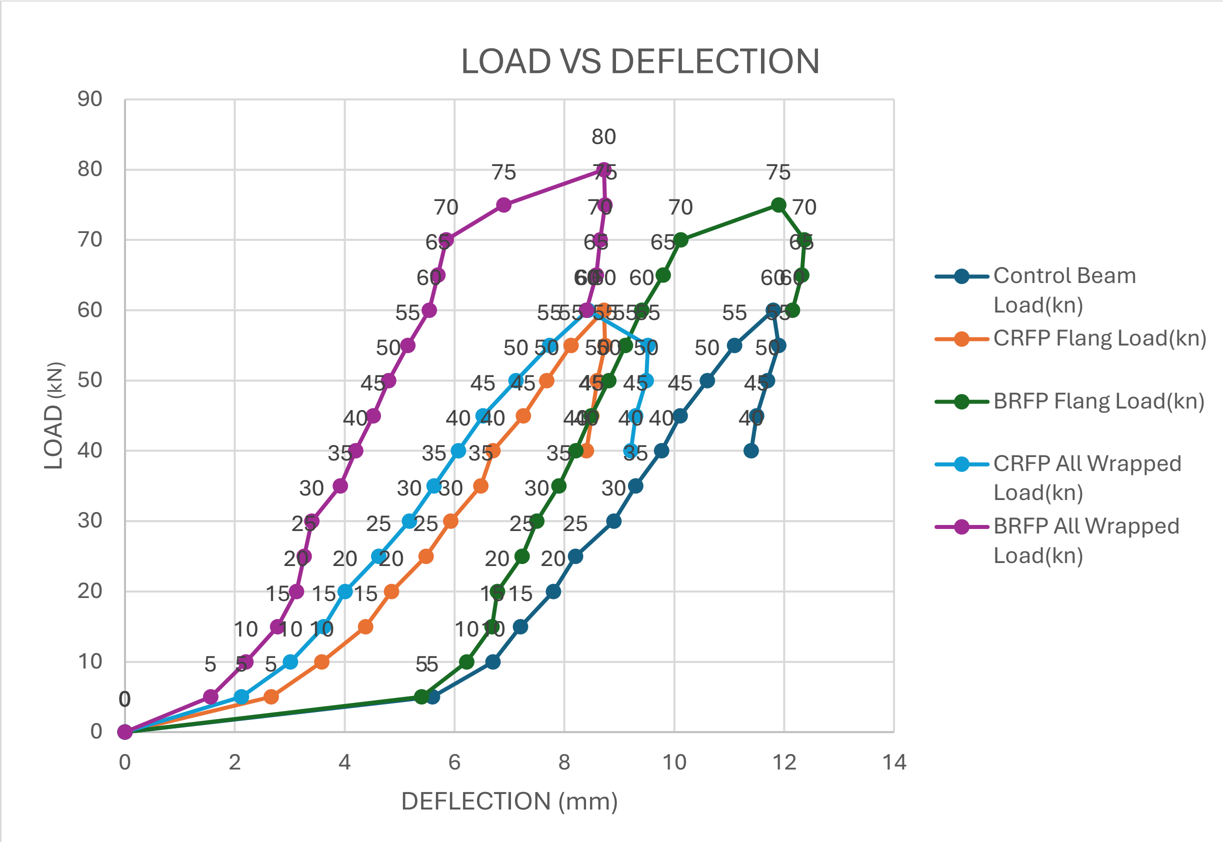


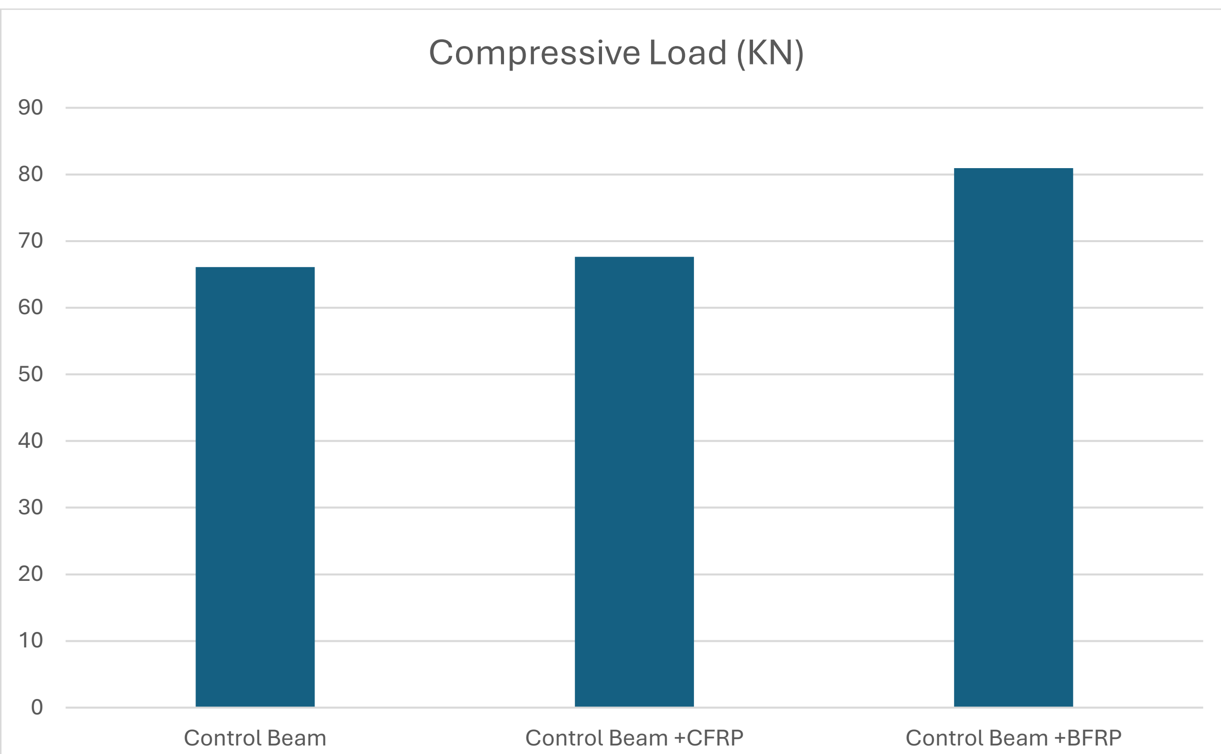
TESTING & RESULTS OF CONTROL BEAM WITH ALL WRAPPED BFRP



4. RESULT AND DISCUSS

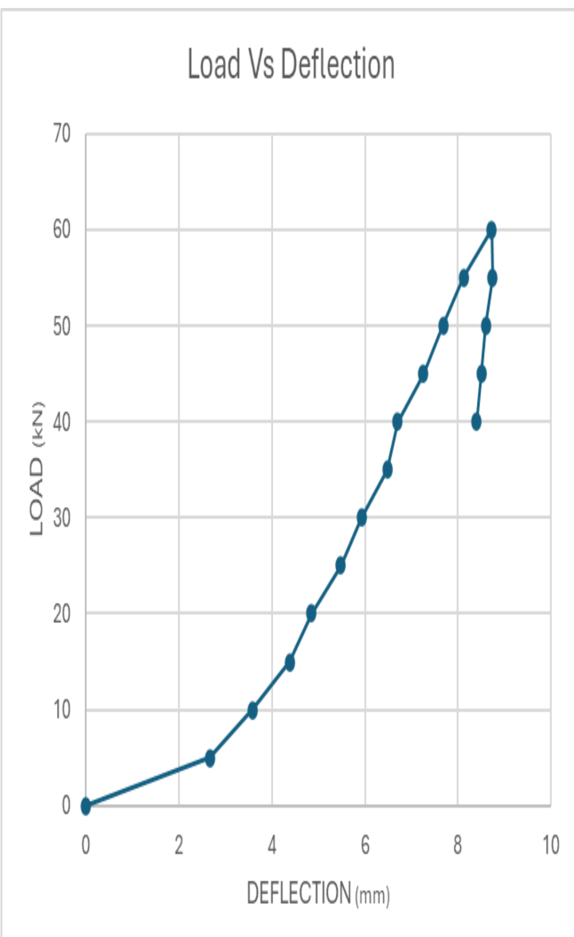
Control Beam		CRFP Flang		BRFP Flang		CRFP All Wrapped		BRFP All Wrapped	
Deflection (mm)	Load (KN)	Deflection (mm)	Load (KN)	Deflection (mm)	Load (KN)	Deflection (mm)	Load (KN)	Deflection (mm)	Load (KN)
0	0	0	0	0	0	0	0	0	0
5.6	5	2.66	5	5.4	5	2.12	5	1.56	5
6.7	10	3.58	10	6.22	10	3.01	10	2.2	10
7.2	15	4.38	15	6.68	15	3.62	15	2.78	15
7.8	20	4.85	20	6.78	20	4.01	20	3.12	20
8.2	25	5.48	25	7.23	25	4.62	25	3.26	25
8.9	30	5.93	30	7.5	30	5.18	30	3.4	30
9.3	35	6.48	35	7.9	35	5.63	35	3.92	35
9.77	40	6.7	40	8.21	40	6.07	40	4.2	40
10.11	45	7.25	45	8.49	45	6.52	45	4.52	45
10.6	50	7.68	50	8.81	50	7.12	50	4.8	50
11.1	55	8.12	55	9.11	55	7.73	55	5.15	55
11.8	60	8.72	60	9.41	60	8.43	60	5.54	60
11.9	55	8.74	55	9.8	65	9.52	55	5.7	65
11.7	50	8.6	50	10.12	70	9.49	50	5.85	70
11.5	45	8.5	45	11.9	75	9.3	45	6.9	75
11.4	40	8.4	40	12.37	70	9.21	40	8.72	80
				12.32	65			8.74	75
				12.15	60			8.65	70
								8.58	65
								8.4	60

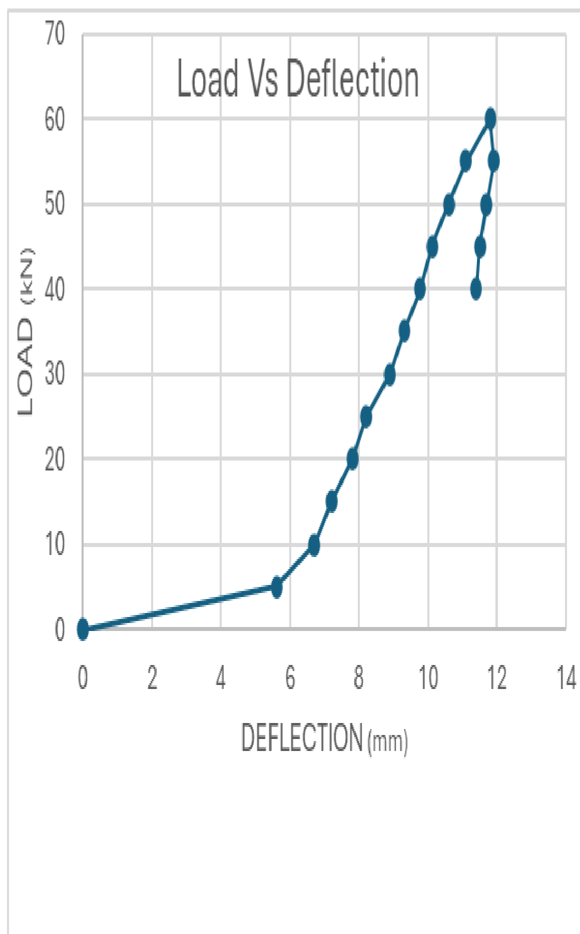

LOAD VS DEFLECTION
LOAD (kN)
DEFLECTION (mm)
Control Beam Load(kn)
CRFP Flang Load(kn)
BRFP Flang Load(kn)
CRFP All Wrapped Load(kn)
BRFP All Wrapped Load(kn)


Compressive Load (KN)
Control Beam
Control Beam +CFRP
Control Beam +BFRP

CRFP Flang	
Deflection (mm)	Load (KN)
0	0
2.66	5
3.58	10
4.38	15
4.85	20
5.48	25
5.93	30
6.48	35
6.7	40
7.25	45
7.68	50
8.12	55
8.72	60
8.74	55
8.6	50
8.5	45
8.4	40

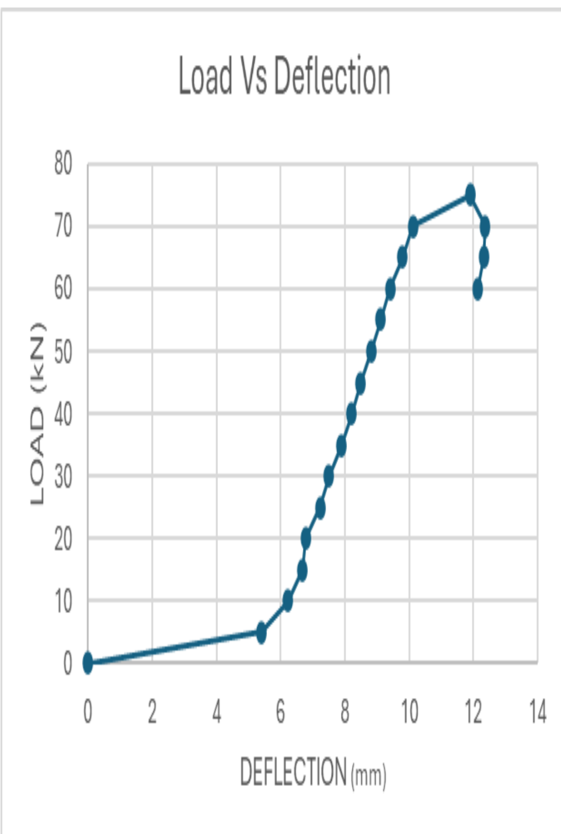
Control Beam	
Deflection (mm)	Load (KN)
0	0
5.6	5
6.7	10
7.2	15
7.8	20
8.2	25
8.9	30
9.3	35
9.77	40
10.11	45
10.6	50
11.1	55
11.8	60
11.9	55
11.7	50
11.5	45
11.4	40

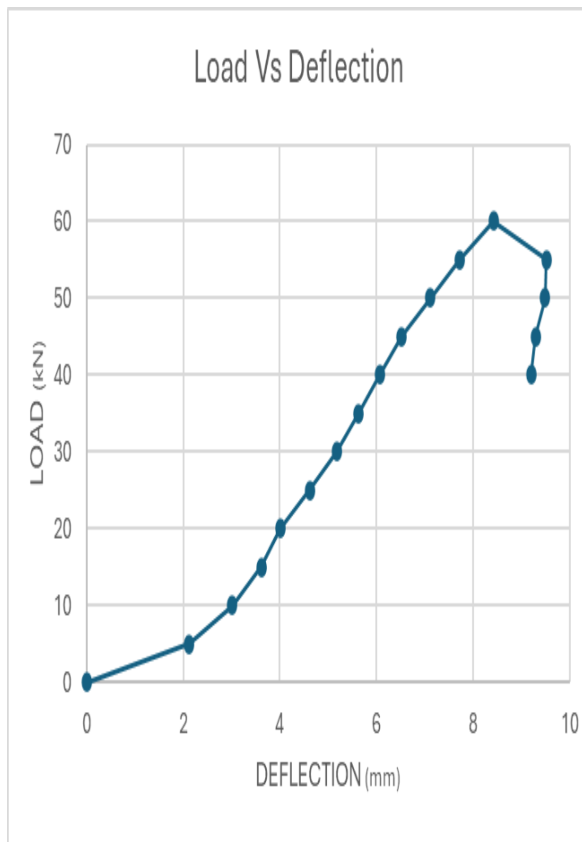




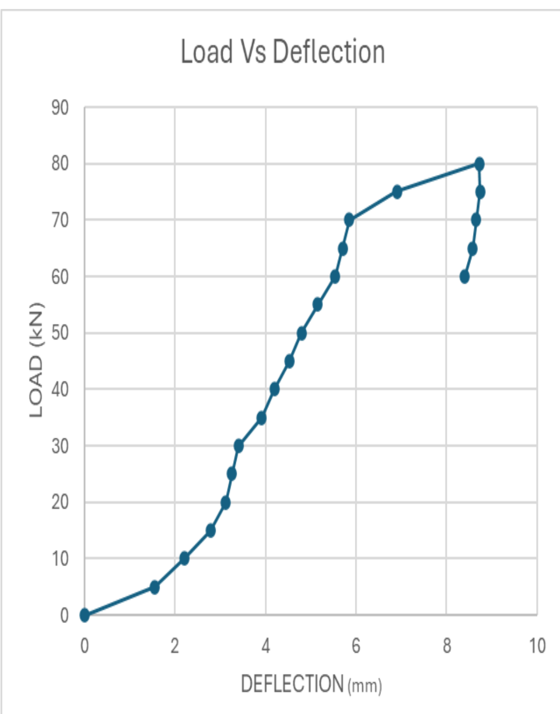
BRFP Flang	
Deflection (mm)	Load (KN)
0	0
5.4	5
6.22	10
6.68	15
6.78	20
7.23	25
7.5	30
7.9	35
8.21	40
8.49	45
8.81	50
9.11	55
9.41	60
9.8	65
10.12	70
11.9	75
12.37	70
12.32	65
12.15	60

CRFP All Wrapped	
Deflection (mm)	Load (KN)
0	0
2.12	5
3.01	10
3.62	15
4.01	20
4.62	25
5.18	30
5.63	35
6.07	40
6.52	45
7.12	50
7.73	55
8.43	60
9.52	55
9.49	50
9.3	45
9.21	40





BRFP All Wrapped	
Deflection (mm)	Load (KN)
0	0
1.56	5
2.2	10
2.78	15
3.12	20
3.26	25
3.4	30
3.92	35
4.2	40
4.52	45
4.8	50
5.15	55
5.54	60
5.7	65
5.85	70
6.9	75
8.72	80
8.74	75
8.65	70
8.58	65
8.4	60



5. CONCLUSION

Research on Fiber Reinforced Polymer (FRP) sheets, such as Basalt Fiber Reinforced Polymer (BFRP) and Carbon Fiber Reinforced Polymer (CFRP), in the strengthening of steel I-beams has proven substantial increases in structural performance. The materials exhibit high resistance to corrosion and chemical attacks, justifying their suitability in aggressive environments. Additionally, the fact that they are flexible justifies ease of application on curved and irregular surfaces, breaking free from limitations related to conventional steel plate bonding.

Experimental studies and finite element simulations have revealed that both BFRP and CFRP are capable of enhancing the flexural stiffness and strength of steel I-beams. CFRP, being more tensile in nature, offers great load-carrying capacity improvements, while BFRP provides a low-cost option without sacrificing performance. The use of these FRP materials has been proved and established in numerous studies, verifying their effectiveness in restoring as well as enhancing the structural properties of steel beams.

1. Deflection Comparison

Control Beam (No FRP): The deflection in the control beam is highest in comparison to any FRP application throughout all stages of loading. This indicates that the control beam, without the use of any strengthening material, has the greatest deformation under load.

CFPP and BFRP on Flanges Only: In the case of CFRP and BFRP sheets applied only to the flanges, the beams have smaller deflections compared to the control beam. This illustrates that CFRP and BFRP both strengthen the stiffness of the beam when the application is done only to the flanges.

CFRP indicates a greater deflection reduction than BFRP at the same load values. For instance, at a load of 40 kN, the deflection of the CFRP flange beam is about 8.21 mm, while that of the control beam is 9.77 mm, a significant improvement.

Fully Wrapped CFRP and BFRP: When the beams are completely wrapped using CFRP or BFRP, deflection is the smallest for all possibilities. This means that full wrapping, especially with CFRP, results in a stiffer structural behaviour, restraining deflection at higher loads.The entirely wrapped CFRP beams exhibit the minimum deflections at all loading steps, even when compared to the flanged applications. This indicates that complete wrapping plays an important role in enhancing the beam's overall stiffness and strength. For example, under a load of 80 kN, the deflection of the entirely wrapped CFRP beam is about 8.4 mm, and that of the control beam is 12.32 mm.

2. Load-Carrying Capacity

Improvement of Load Capacity with FRP: With the inclusion of both CFRP and BFRP, the load-carrying capacity of the beams is higher compared to the control beam. This can be seen in the way beams having FRP (both on flanges and fully wrapped) will have greater load-bearing values, with CFRP, particularly when applied in a fully wrapped form, showing the maximum improvement in load-carrying capacity.

For example, under deflection of 10 mm, the control beam is loaded with 50 kN, whereas the CFRP fully wrapped beam can withstand higher load up to 70 kN under the same deflection.

3. Effectiveness of CFRP vs. BFRP

CFRP vs. BFRP: Overall, CFRP performs better in both deflection control and load-carrying capacity than BFRP. Though both are good at enhancing the performance of the beam, CFRP provides better outcomes at every loading stage. This is reflected in the reduced deflections and increased load-carrying capacities experienced in CFRP beams, particularly when wrapped to the full extent.

4. Trends in Data

Optimized Effectiveness with Complete Wrapping: Complete wrapping of the beams, irrespective of whether CFRP or BFRP is applied, gives the maximum enhancement of the beam's structural performance. The beams fully wrapped, particularly the CFRP-wrapped ones, exhibit the most deflection resistance against applied loads.

Difference Between Flange-only and Full-Wrap Applications: While reinforcing the flanges only enhances the performance over the control beam, full wrapping the beam offers a more even reinforcement and heavily enhances both deflection control and load-carrying capacity.

The use of both CFRP and BFRP on the I-section beams results in decreased deflections and increased load-carrying capacities than those of the control beam. Complete wrapping of the beams offers the highest gains, especially with the use of CFRP. CFRP exhibits better performance in deflection control and load-carrying capacity than BFRP. Hence, to achieve maximum strength and stiffness of I-section beams, full wrapping with CFRP is the best, followed by CFRP and BFRP flange-only applications.

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