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Experimental and Numerical Assessment of Flexural Shear Behavior of RC Beams Enhanced using Hybrid CFRP–GFRP U-Wrap System

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Abstract

This study examines the Reinforced Concrete beams strengthened in Flexural-shear using a hybrid Fibre Reinforced Polymer (FRP) system that combines carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) in a U-wrap configuration. Six beams totally were made and the results were tested under 4 point bending moment using LVDT, in which three beams were of control beams without strengthening and another three externally wrapped using hybrid CFRP-GFRP U-wraps. The beams were built using M30 grade concrete, 2 x 10 mm tensile bars, and 2 x 8 mm compression bars. The hybrid strengthening configuration featured an initial layer of GFRP, followed by an outer layer of CFRP bonded using Araldite LY556 epoxy and Hardener HY951. The testing results demonstrate a considerable increase in load carrying capability, stiffness, and crack control when compared to unstrengthened beams. The flexural response of both control and strengthened beams was simulated using finite element modeling with ANSYS Mechanical. With respect to final load, deflection patterns, and stress-strain distribution, the numerical results were nearly identical to the experimental findings. The hybrid FRP wrapping system significantly improved flexural performance, including increased ductility and delayed crack propagation. The study shows that the CFRP-GFRP hybrid U-wrap system is an efficient and cost-effective alternative to single-type FRP reinforcement in RC beam retrofitting applications.

Keywords: Hybrid FRP; CFRP-GFRP U-wrap; reinforced concrete beams; flexural performance; finite element modelling; structural retrofitting

INTRODUCTION

Overloading, corrosion, and environmental exposure often deteriorate the strength and serviceability of reinforced concrete (RC) structures. Traditional repair methods like steel jacketing and section enlargement increase dead load and require extensive labor. Fiber-Reinforced Polymer (FRP) composites have become good options because they are strong even when stretched, light, and don't rust. Carbon FRP (CFRP) provides improved strength and stiffness at a higher cost, whereas Glass FRP (GFRP) is less expensive but less rigid. The combination of CFRP and GFRP achieves a balance of performance and cost, with GFRP adding ductility and CFRP increasing stiffness [1].

The flexural-shear behavior of RC control and strengthened beams reinforced using hybrid CFRP-GFRP U-wrap system is assessed in this study through experimental investigation and simulation analysis. Six beams were subjected to four-point bending to investigate load capacity, deflection,

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and crack patterns, with ANSYS Mechanical used to validate the experimental findings. The results show that hybrid FRP systems increase flexural strength, reduce premature debonding, and provide a dependable, cost-effective strengthening method for structural rehabilitation [2].

LITERATURE REVIEW

Recent research has emphasized the increasing usage of (FRP) composites to enhance both flexural and shear capacities of RC beams. Researchers such as Al-Mahaidi (2020) and Grelle (2021) have shown that externally bonded CFRP laminates greatly improve load-bearing capacity and stiffness while delaying fracture propagation [3]. However, premature debonding failure and brittle conduct frequently limit their entire potential To address this, hybrid FRP systems mixing carbon and glass fibres have gained popularity for their balanced mechanical response. Ahmed et al. (2022) found that GFRP-CFRP hybrid wraps improve ductility and energy absorption, making them a cost-effective alternative to full CFRP strengthening [4]. Zhang et al. (2023) and Priya & Senthil (2024) found that hybrid U-wrap topologies improved both flexural strength and interfacial bonding between concrete and FRPlayers. Numerical analyses with ANSYS and ABAQUS have also demonstrated the ability of hybrid FRP systems to replicate realistic failure modes with a high correlation to test results. Despite these developments, there is little research on the combined experimental and numerical evaluation of hybrid CFRP-GFRP U-wrap systems under four-point bending. As a result, the purpose of this study is to close that gap by assessing the flexural performance of RC beams upgraded by hybrid FRP wrapping, with an emphasis on the comparative behavior of experimental testing and finite element modelling [5].

Aim

To study the experimental and numerical behavior of reinforced concrete (RC) beams strengthened with a hybrid Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) U-wrap system under flexural-shear loading conditions, as well as its effectiveness in improving overall structural performance when compared to conventional strengthening methods.

Objectives:

- To design, cast, and strengthen RC beams utilizing a hybrid CFRP-GFRP U-wrap arrangement.
- Conducting experimental testing to evaluate the flexural and shear performance of control and improved beams.
- Developed ANSYS Mechanical finite element models to simulate hybrid strengthened beams and compare them to experimental data.
- To contrast the load-deflection response, crack morphologies, and strain distribution between experimental and numerical investigations.
- To evaluate the hybrid CFRP-GFRP U-wrap system as a cost-effective alternative to single-type FRP strengthening for RC beam retrofitting applications.

LABORATORY INVESTIGATION

Constituent Materials of Concrete

Concrete is a composite material consisting mostly of cement, fine aggregate, coarse aggregate, and water, which are blended in particular proportions to create the necessary strength and workability. In this investigation, OPC was employed as a binding material, with M sand as the fine aggregate and crushed granite as the coarse aggregate. To assure uniformity and quality, both mixing and curing were done using potable water. Proper selection and proportioning of these constituent elements are critical to providing the appropriate mechanical and durability qualities of concrete. The properties of cement and aggregates adopted for the concrete mix are presented in Table 1 and Table 2, respectively, ensuring the required strength and durability characteristics.

Beam Design and Details

The experiment used six reinforced concrete (RC) beams of size 100×200×1500mm.The RC beam design were shown in Figure 1. Three of these were designated as control beam elements (unstrengthened), while the other three beams were strengthened using a Hybrid CFRP-GFRP U-wrap system.

Table 1. Properties of cement.

S.N.	Test conducted	Values
1	Grade of cement	53 Grade
2	Specific gravity	3.13
3	Initial Setting time	39 minutes
4	Standard Consistency	33%
5	Fineness	7.5%

Table 2. Properties of aggregates.

S.N.	Name of test	FA	CA
1	Specific Gravity	2.65	2.70
2	Bulk Density (kg/m³)	1685	1549
3	Fineness Modulus	2.65	7.20
4	Sieve Analysis	Zone II	Zone II
5	Water Absorption	1.0%	1.27%

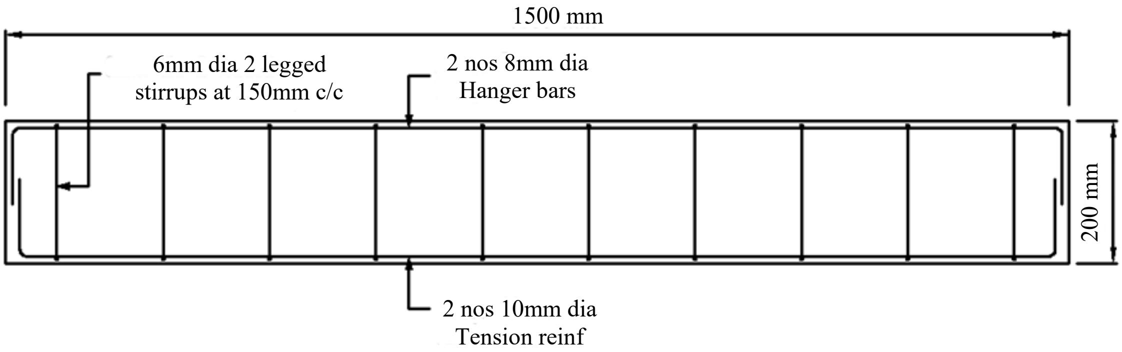


Figure 1. Reinforcement details of beam.

The beams were constructed for flexure using limit state ideas in compliance with IS 456:2000. The reinforcement was made of two 10 mm dia bars in the tension region and two 8 mm dia bars in the compression area, along with 6 mm stirrups spaced 100 mm c/c throughout the shear span [6]. The beams were cast from M30 grade concrete, cured for 28 days, and finally it was tested under four-point bending loading fram using LVDT to assess flexural-shear strength and deformation behavior. Basic tests such as slump cone, cube, and cylinder tests were performed, and the images are given in Figure 2.

Material Properties

The Water-to-cement ratio is 0.45, and the concrete was mixed with a proper proportion to maintain a goal compressive strength of 30 MPa after 28 days. Sand and crushed granite CA with a highest size of 20 mm were employed, as well as ordinary Portland cement. The average cube strength achieved was 31.2 MPa. The yielded strength of reinforcing steel for 10 mm & 8 mm bars was Fe 500The GFRP sheet's ultimate strength was 1100 MPa, with the elastic modulus of 72 GPa and ultimate strain value is 2.4%. The bonding glue utilized was Araldite LY556 epoxy resin with Hardener HY951, which was blended at a weight ratio of 10:1 to ensure uniform bonding between the FRP layers and the concrete surface [7].

Strengthening Configuration

To increase adhesive bonding in the hybrid wrapping arrangement, each strengthened beam was surface-prepared by cleaning, roughening, and eliminating laitance. The initial layer of GFRP sheet was placed to the tension zone in a U-wrap pattern, covering 420 mm along the beam span and 1300 mm across the beam depth, guaranteeing complete side coverage. Following the curing of the first layer, the second layer of CFRP sheet was connected to the GFRP with the same epoxy glue. This hybrid structure sought to combine GFRP's ductility with CFRP's stiffness and strength, resulting in good confinement and crack management around supports and flexural regions [8].

TEST SETUP AND INSTRUMENTATION

Complete strengthened hybrid beams were evaluated using four-point loading frame in a 1000 kN loading frame. The clear span between supports was kept at 1200 mm, with the two loading points located symmetrically one-third of the way from each support [4]. Deflections during loading were recorded using Linear Variable Differential Transformers (LVDTs) deployed in midspan and quarter-span positions. An Electrical resistance along with a strain gauge were installed along the concrete surface and FRP layers to monitor strain buildup. The load was gradually delivered using a hydraulic jack, as illustrated in Figure 3, and the deflections were measured using a load data cell attached to a data collection system.

Testing of Control Beams

To establish the baseline flexural performance, the control beams were cast without any external strengthening and tested in a four-point bending arrangement. The beams, measuring 100 × 200 × 1500 mm, were mounted on basic supports with an effective span of 1200 mm. At the other end, we used to monitor a hydraulic jack, which is used to gradually release the load until failure, and deflection values were taken at the mid-span. Crack initiation, propagation, and failure patterns were monitored closely during the test [9] . The control beam data are used as a reference to compare the performance of hybrid FRP-strengthened specimens. Table 3 shows the load deflection values for the control beam and Figure 4 illustrates the average load–deflection response of the control beam

Figure 2. Concrete mixing for slump cone and cube.

Figure 3. Hybrid U-wrap testing.

Table 3. Load –deflection of control beam.

Control beam (Flexure-shear)			
Load (kN)	**LVDT1 (mm)**	**LVDT2 (mm)**	**LVDT3 Near Center (mm)**
0	0	0	0
5	0.310	0.340	0.450
10	0.710	0.750	0.950
15	1.120	1.180	1.460
20	1.580	1.640	2.020
25	2.020	2.090	2.570
30	2.480	2.560	3.130
35	2.950	3.030	3.720
40	3.430	3.510	4.320
45	3.920	4.000	4.880
50	4.410	4.490	5.430
55	4.930	5.010	6.000
60	5.420	5.510	6.520
65	5.910	6.020	7.030
70	6.420	6.520	7.580
75	6.940	7.050	8.050
80	7.480	7.600	8.740
82	8.430	8.679	9.435

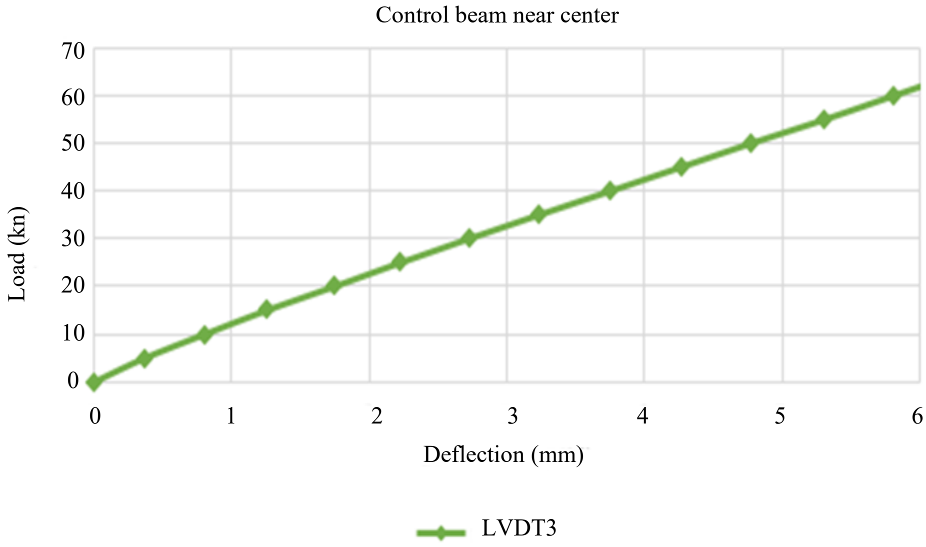


Figure 4. Average control beam load versus deflection

Assessment of Strengthened Beams

To enable direct comparability, the strengthened beams were refitted with hybrid CFRP-GFRP laminates in a U-wrap configuration and evaluated using the same four-point bending arrangement as the control specimens. Each specimen was equipped with LVDTs and strain gauges at critical spots (at the mid-span and at the FRP layers) to record deflection and strain histories from monotonic loading till failureLoad was applied gradually while fracture start, propagation, FRP debonding (if any), and ultimate failure mode were monitored and reported. The results of these tests were as compared with the control beams to determine the increases in loaded capacity, stiffness, ductility, and crack control provided by the hybrid U-wrap strengthening. Table 4 displays the load deflection values for the reinforced beam, whereas Figure 5 depicts the average load and the deflection for the stronger beam (flexure shear).

Table 4. Load–deflection of strengthened beam.

Hybrid beam (Flexure-shear)			
Load (kN)	LVDT1 (mm)	LVDT2 (mm)	LVDT3 Near Center (mm)
0	0	0	0
5	0.385	0.450	0.580
10	0.625	0.710	0.950
15	0.865	0.980	1.390
20	1.140	1.300	1.880
25	1.420	1.630	2.350
30	1.720	1.950	2.850
35	2.010	2.280	3.370
40	2.340	2.640	3.930
45	2.690	3.000	4.520
50	3.050	3.380	5.080
55	3.420	3.760	5.650
60	3.780	4.120	6.250
65	4.160	4.510	6.780
70	4.550	4.930	7.340
75	4.940	5.350	7.880
80	5.360	5.790	8.470
85	5.780	6.250	9.050
90	6.230	6.730	9.640
95	6.700	7.240	10.080
100	7.150	7.740	10.530
105	7.570	8.200	10.920
110	7.890	8.600	11.230
115	8.160	9.160	11.460
120	8.347	9.678	11.570

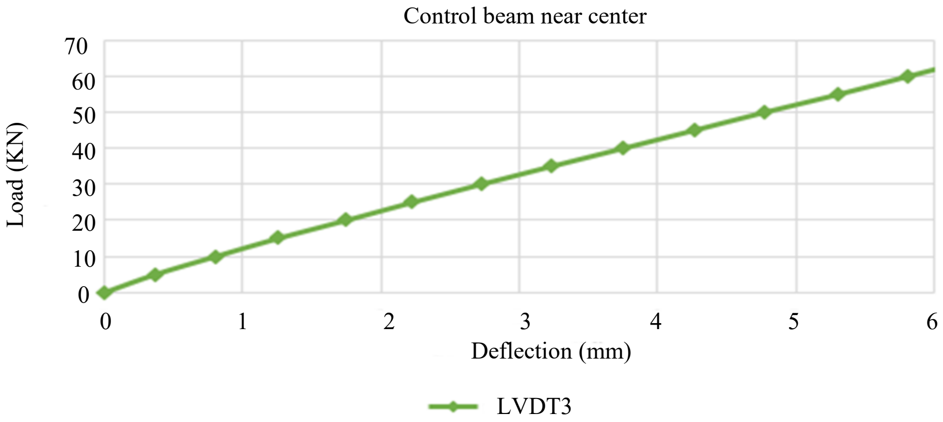


Figure 5. Average hybrid load versus deflection.

Observations

The control beams showed normal flexural cracking in the tension zone, which progressed fast to concrete crushing at the compression face. The hybrid U-wrapped beams, on the other hand, demonstrated delayed crack onset, lower crack widths, and increased load-carrying capacity. The initial cracks emerged at the midspan, but their expansion was limited by the containment provided by the hybrid FRP layers. At comparable load values, the reinforced beams showed increased stiffness and decreased deflection. The outer CFRP layer debonded only near ultimate load, indicating excellent stress transfer between GFRP, CFRP, and the concrete substrate.The Crack patterns of Hybrid U-Wrap pattern has been clearly shown in Figure 6.

Figure 6. Hybrid crack patterns.

Evaluation of Results

The test observations illustrated that the hybrid CFRP-GFRP U-wrapped beams demonstrated much better flexural performance than the control specimens. The reinforced beams exhibited delayed crack onset, reduced crack widths, and increased load-carrying capability while improving stiffness and ductility. At maximal load, mid-span deflections were much smaller, indicating efficient confinement and energy absorption [6] .The ANSYS Mechanical simulation closely matched the experimental results, displaying identical stress distribution and crack propagation patterns with just slight differences due to idealized modeling assumptions. Overall, the hybrid FRP system effectively blended CFRP's high strength and GFRP's flexibility, resulting in an optimal and cost-effective solution for strengthening RC beams. Figure 7 shows the comparision of Final load Hybrid FRP along with the ultimate Control beam.

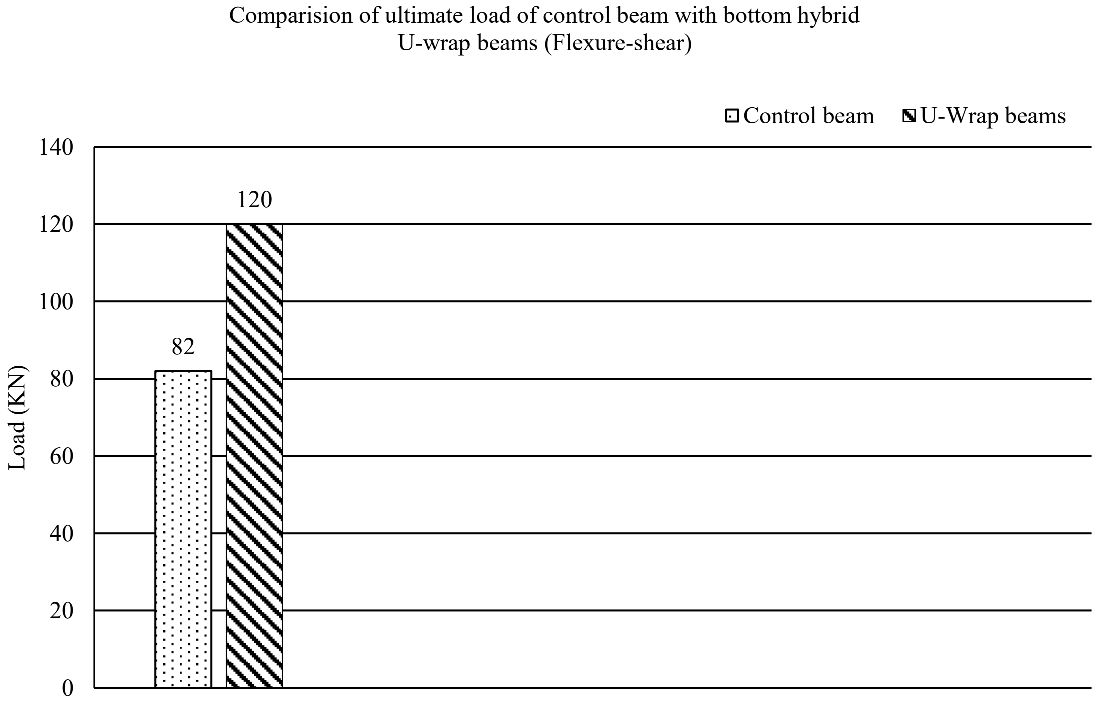


Figure 7. Comparison of ultimate flexural loads of hybrid FRP–wrapped beams and control beams.

NUMERICAL ANALYSIS

Modelling Overview

Experimentally tested RC beams' flexural performance was simulated numerically using ANSYS Mechanical [10]. The FE model was done to reproduce the geometry, boundary conditions, material behavior, and loading configuration of both the control and hybrid CFRP-GFRP reinforced beams. The approach intended to anticipate load-deflection response, stress distribution, and failure patterns, allowing for comparison with experimental data. The model included nonlinear properties for concrete, reinforcing steel, and FRP composites to accurately represent cracking, yielding, and interface behavior. Geometry construction, meshing, material specification, contact assignment, loading, and solution were all carried out sequentially during the modeling process [11].

Material Properties

The material's nonlinear characteristics were defined based on experimental data. For M30 grade concrete, the elasticity was taken as 27 GPa, Transverse strain ratio as 0.2, and the Crushing strength as 30 MPa. The stress-strain relationship was defined using the multilinear isotropic hardening model, with tension cut-off representing cracking behaviour. The reinforcing steel bars had a 500 MPa yield strength, a 200 GPa elastic modulus, and a 0.3 Poisson's ratio. We employed orthotropic elastic material models for the FRP layers. The GFRP sheet had 72 GPa, a Poisson's ratio of 0.27, and a ultimate strength of 1100 MPa, whereas the CFRP sheet had an modulus of 230 GPa, a Poisson's ratio of 0.28, and an ultimate tensile strength of 3800 MPa. A small contact layer with adequate stiffness was used to represent the epoxy interface between the hybrid FRP and concrete, resulting in a realistic bond simulation [12].

Boundary Conditions and Loading

To prevent rigid body motion, simply supported boundary conditions were implemented at both beam ends, with one support constrained vertically and the other restrained vertically and horizontally. Loading was provided using two-point loads at one-third of the span from each end, imitating the experimental four-point bending configuration. To achieve steady nonlinear solution convergence, the load was delivered incrementally using a displacement-controlled approach. Contact interactions were identified between the FRP layers and the concrete surface to track stress transmission and probable debonding zones [16]. The analysis was carried out under static structural circumstances until ultimate failure, with essential outputs such as load-deflection curves, crack outlines, and major stress distributions retrieved for comparison purposes and the designed Strengthened beam using Hybrid FRP is represented in the below Figure 8.

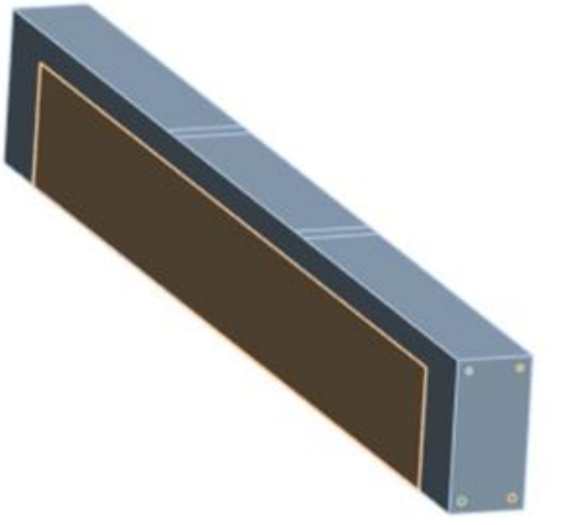
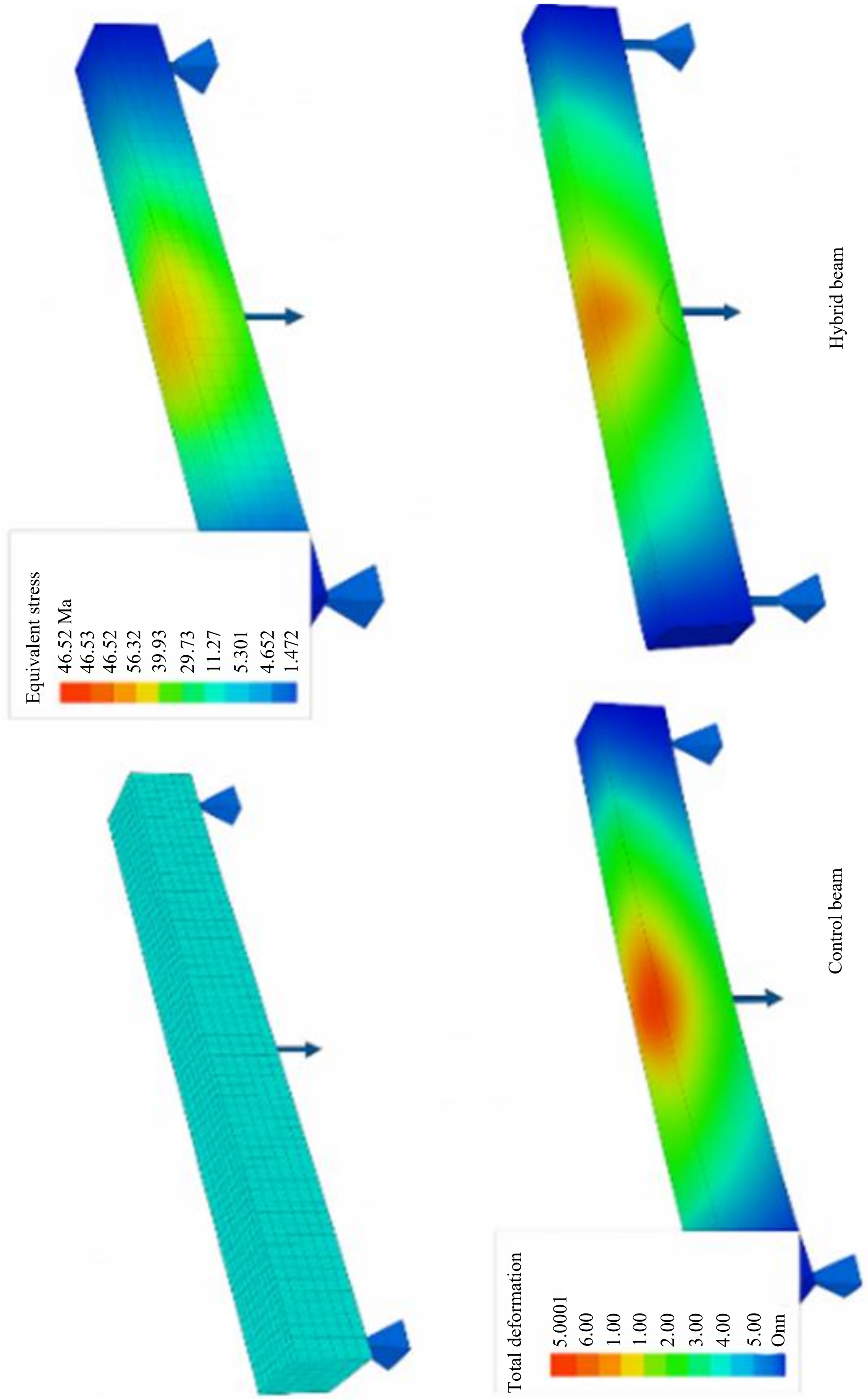


Figure 8. Strengthened beam with Hybrid FRP (CFRP & GFRP) U wrap pattern.



Control beam

Hybrid beam

Figure 9. Analytic analysis of control vs hybrid beam

RESULTS AND DISCUSSION

Experimental and computational results showed that hybrid CFRP-GFRP U-wrapped beams had better flexural performance than control specimens. The reinforced beams exhibited delayed crack onset, smaller crack widths, and increased load-carrying efficiency with diminished mid-span variation, indicating increased stiffness as well as ductility. Stress redistribution throughout the hybrid system resulted in increased energy absorption and deformation resistance [13]. The ANSYS Mechanical simulations closely matched the experimental results, with a load-deflection variation of less than 10%. The hybrid U-wrap structure efficiently reduced stress concentration ensured uniform stress distribution, and greatly increased overall ultimate strength and serviceability of RC beams. The analytical comparison between control and hybrid beams is presented in Figure 9, highlighting the improvement in load-carrying capacity and overall structural performance of the strengthened specimens.

COMPARISON OF EXPERIMENTAL AND ANALYTICAL CORRELATION

The experimental and computational studies were highly consistent, demonstrating the accuracy of the finite element simulation carried out in ANSYS Mechanical. The predicted ultimate load values were within 5-8% of the experimental findings, indicating the model's dependability.Hybrid CFRP-GFRP U-wrapped beams showed a significant flexural improvement over control specimens—about 45% experimentally and 42% numerically [14]. While the FE model marginally underestimated mid-span deflection at higher loads due to idealized conditions, the overall load-deflection trend, crack formation, and strain distribution were very similar to the tests. Both results demonstrated the hybrid system's combined advantages of CFRP stiffness and GFRP ductility, including delayed failure and excellent stress redistribution. Minor discrepancies were related to practical bonding flaws, supporting the model's applicability for accurate prediction and future parametric research [15].

Summary

The study found that hybrid CFRP-GFRP U-wrap strengthening improved the moment-carrying capacity of reinforced concrete beams considerably while in combination with the unstrengthened controls. The manual results revealed higher load-carrying capacity, reduced deflection, delayed fracture formation, and improved ductility, while numerical analysis with ANSYS Mechanical closely matched the observed behavior with little variance. The hybrid structure successfully integrated the high stiffness of CFRP with the ductility of GFRP, resulting in improved stress redistribution and energy absorption. Overall, experimental and analytical results revealed that the hybrid U-wrap system is a dependable, efficient, and low-cost technique for increasing the structural behaviour and the life time of RC beams.

CONCLUSION

This work conducted an experimental and computational work of the flexural-shear performance characteristics of RC beams reinforced using a hybrid CFRP-GFRP U-wrap system. Under four-point bending, six beams were examined, three of which were control and three of which were strengthened. The experimental observations and finite element analysis lead to the following conclusions:

1. The hybrid CFRP-GFRP U-wrap arrangement increased ultimate load capacity by 40% compared to the control beams.
2. The hybrid system effectively confined the beams, resulting in lower deflection, delayed crack start, and smaller crack widths.
3. Combining GFRP and CFRP layers increased ductility and energy absorption, resulting in gradual rather than brittle failure behavior.
4. ANSYS Mechanical's finite element analysis accurately predicted the load-deflection response and crack pattern, which matched testing results.
5. The simulation's idealized boundary conditions and perfect bond assumptions caused slight discrepancies between experimental and numerical results.
6. The study finds that the hybrid FRP U-wrap system effectively strengthens RC beams by combining the rigidity of CFRP and the flexibility of GFRP.

Overall, the hybrid wrapping technique is effective for structural retrofitting applications that require high strength, ductility, and cost effectiveness. To improve performance and endurance, future study could focus on improving the layer sequence, fiber orientation, and interface bonding characteristics.

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