

Performance And Failure Behavior Of Prestressed Concrete Beams Strengthened With Multi-Layer CFRP: Experimental And Numerical Investigation

Hayder Abdul Hadi Abdul Razzaq¹

¹PhD in structural engineering, A' Lecturer in Islamic University Al-Najaf, College of Engineering Technology, Department of Building and Construction Technology
Email: hayder.a.alhilo@iunajaf.edu.iq, ORCID: hayder alhillu: 0009-0003-9047-4612

Abstract:

This study presents a comprehensive experimental and analytical investigation into the flexural behavior and sustainability implications of reinforced prestressed concrete (PC) beams strengthened externally with Carbon Fiber Reinforced Polymer (CFRP) laminates. The research aimed to evaluate the synergistic effects of varying prestressing force levels (150 kN and 200 kN) and the number of CFRP layers (one, two, and three) on structural performance and long-term durability. Seven full-scale beams were tested under a four-point bending setup. The results demonstrate that CFRP strengthening significantly enhanced the ultimate load-carrying capacity. The experimental work shown increases ranging from 35% to 106.4% compared to the unstrengthened control beam. A corresponding rise in post-cracking flexural stiffness was also observed. However, this substantial gain in strength was accompanied by a significant reduction in ductility, shifting the failure mode from ductile concrete crushing in the control beam to brittle CFRP rupture and interfacial debonding. CFRP strengthening contributes positively to sustainability as it uses less material, reduces the frequency of maintenance, extends the service life of the structure, and decreases carbon emissions compared to conventional retrofitting. Apart from addressing the fundamental trade-off between strength and ductility, the research highlights that further refinements in the application of CFRP will enhance structural efficiency and improve the sustainability of building designs.

Keywords: Prestressed Concrete, CFRP Strengthening, Flexural Behaviour, Ductility, Debonding, Sustainability, Environmental Impact.

1. Introduction The construction sector has developed rapidly, leading to increased economic and material costs; therefore, there is an urgent need for structural components that are stronger and more durable. Engineers have recognized the excellent properties of composite materials since the last century, leading to the development of several types of modern composites, including Fiber Reinforcement Polymer. CFRP bars and sheets work better than rebar in beams and columns (El Gendy et al., 2025). These measures will reduce harmful carbon emissions and ensure that the manufacturing of these materials complies with environmental and global warming regulations. FRP is key to green building. This trend is not limited to replacing components, but also involves transforming the way entire structural elements are designed to be innovative and intelligent (Wang, 2025). The integration of traditional and advanced materials requires rigorous mathematical analysis, and computational models are used to predict the behavior of brittle concrete to ensure structural safety and accuracy (Işıklı, 2025). The primary focus is not only on restoring old buildings but also on identifying effective methods for constructing new buildings and structures. Older buildings face significant risks from ground shaking; therefore, strengthening them is essential to protect lives (Hassas & Bordbar, 2025). The use of CFRP is an effective solution for strengthening and rehabilitating existing structures. Experimental studies on railway bridges strengthened with CFRP sheets have demonstrated their effectiveness under heavy moving loads and their long-term durability (Näsbom et al., 2024). To achieve optimal performance, it is

necessary to understand the adhesion mechanisms between polymer materials and existing concrete, as well as to develop effective bonding techniques. Additionally, engineered cementitious composites (ECC) enhance the compatibility and performance of CFRP sheet strengthening systems by providing improved ductility and crack control (Hu et al., 2024). However, there is an important drawback: adding multiple layers of carbon fiber-reinforced polymer (CFRP) significantly increases the beam's resistance to applied loads—by up to 106%, as reported in this study—but at the same time makes the beam excessively stiff. This excessive stiffness leads to sudden and brittle failure modes, characterized by unexpected fractures, which pose a serious safety risk under seismic loading. Therefore, such an approach should be avoided. Properly designed CFRP strengthening should enhance load-carrying capacity while preserving sufficient ductility and deformation capacity to ensure structural safety. Mixing tight cable inside concrete (prestressing) with CFRP outside is great idea. Tight wires stop cracks early and CFRP stops rust later. This makes beams last very long with little care. It saves money and stuff over time. This proposal aligns with economic considerations that emphasize extending the service life of structures. This study demonstrates that achieving efficient performance and long-term durability is just as important as the use of environmentally friendly materials. Mixing different things is heart of new building. Putting fibers in concrete and using plastic rods makes best of both (Shi et al., 2024). This matches trend of using light wall panels to build fast and green (Sah et al., 2024). Studies look at how fibers help strong beams bend better (Koura et al., 2024). So, knowing how beams with CFRP sheets bend and hold together is key to make sure they stick well (Yuan et al., 2024).

However, previous studies have overlooked certain aspects. Most have focused on simple beams or walls, while neglecting beams equipped with internal prestressed cables and external (CFRP) panels. These studies also failed to examine the influence of prestressed wires on the performance of the polymer panels, or to determine whether using a single or triple layer is optimal for practical applications. This study addresses these gaps by testing beams prestressed force with 150 kN and 200 kN tensioned wires and various CFRP layer configurations. The investigation analyzed the fracture behavior of these beams and identified the most effective repair methods, providing engineers with precise guidance for practical implementation. Furthermore, this paper offers new insights into the interaction between tensioned steel cable and adhesive CFRP, highlighting both their individual and synergistic effects.

2. Literature Review

To understand how tight beams with sticky cloth work, we must look at what others did before. Past studies checked many things, from basic bending to shaking loads.

First, knowing how cracks start and grow is key. Khan et al. (2024) looked at beams with cuts (notches) and how patching them helps. This shows that fixing bad spots is first step before making beam stronger. But real world has sudden hits too. Jin et al. (2024) checked how beam joints break when hit hard. This teaches us that beams must be tough, not just strong. Main problem is knowing how much beam will bend. Liu et al. (2024) tested math rules to guess bending in beams with plastic rods and steel. This gives designers tools to know if beam will sag too much. Also, Gupta et al. (2024) made models to guess strength of rusty columns fixed with cloth. This shows cloth works on many shapes, not just beams.

Were also need known if cloth stays on when load goes up and down many times. Tayfur et al. (2024) tested joints with CFRP under moving loads. They used sound sensors to hear cracks. This helps us know if fixing lasts long time. Computers help us test without breaking real things. Covatariu et al. (2024) used computer models to check how to fix big

water tank. This proves computers are good for planning fixes. Mansour et al. (2024) also used computers to see how steel tubes filled with concrete and wrapped in cloth act under shaking loads. For tight beams like ours, Garg et al. (2023) made computer model for tight beams with CFRP sheets. Their model predicts when beam will break very well.

New kinds of light concrete were also tested. Montaser et al. (2022) put sticky cloth on beams made of foam concrete. It worked well. Alkurdi (2021) tested foam beams with glass plastic rods. This shows we can make light and strong beams. Other studies look at making walls in factories. O'Hegarty et al. (2021) checked thin sandwich walls. Wang et al. (2022) tested walls made of parts for quake safety. These show that making things in pieces is fast and good.

Older big studies set the base. Mazaheripour (2015) studied tight beams with mix of glass rods and steel. This is key to know how two metals work together. Noël (2013) checked how bridges with plastic rods handle moving cars over many years. This is vital for real roads.

Summary of Gap:

Even with all this work, something is missing. Review shows many tests on normal beams or columns. But few tests look at tight beams (prestressed) that have steel inside AND CFRP sheets outside at same time. We need to know how these three things (tight wire, steel bar, sticky cloth) talk to each other. This paper fills this hole. We do real tests and computer tests to see how they break and how much they bend.

Table 2.1: Comparison of Past Studies

Reference	Topic	What they fixed	What they found
Khan et al. (2024)	Beams with cuts	Concrete beam	Patching helps stiffness.
Jin et al. (2024)	Sudden impact	Beam joint	How joints break when hit.
Liu et al. (2024)	Guessing sag	Hybrid beam	Rules for bending math.
Gupta et al. (2024)	Rusty columns	Column	Models for old columns.
Tayfur et al. (2024)	Shaking loads	Beam joint	Sound tells crack growth.
Covatariu et al. (2024)	Computer check	Water tank	Computers help plan fix.
Mansour et al. (2024)	Wrapped tubes	Steel tube	Computer model for tubes.
Garg et al. (2023)	Tight beams	Prestressed beam	Model for CFRP beams.
Montaser et al. (2022)	Light foam beam	Foam beam	Cloth makes foam strong.
Alkurdi (2021)	Foam with rods	Foam beam	Glass rods work in foam.
O'Hegarty et al. (2021)	Wall panels	Sandwich wall	Making thin walls is hard.
Wang et al. (2022)	Wall safety	Shear wall	Parts walls are safe.
Mazaheripour (2015)	Mixed rods	Prestressed beam	Glass and steel mix well.
Noël (2013)	Bridge fatigue	Slab bridge	Plastic rods last long.

3. Methodology:

3.1 Plan and Design

This study employed both prototype experiments and computational analysis to investigate the bending behavior and failure mode of strengthened and prestressed beams. The focus was on prestressed beams strengthened with CFRP sheets. Two parameters were examined: the effect of increasing the prestressing force and the number of CFRP layers applied. Seven beams of identical dimensions were fabricated for the study. One beam is "Control Beam" with no cloth. It has tight wire pulled to 150 kN, this is our base to compare. Other six beams have cloth. Were parted them into two teams.

Team 1 (P1): Wire pulled to 150 kN. This prestressed force is like normal load in real buildings. It keeps concrete safe from cracks under service load. •

Team 2 (P2): Strand tensioned to 200 kN. This force is high, near max limit. •
Were chose to see what happens when beam is very tight and then added CFRP sheets. Does it sudden failure? Does it hold more? This helps engineers know safety limits.

In each team, was tested 1, 2, and 3 layers of sheets. Were chosen 1 to 3 layers Because it is used in real-world applications to strengthen beams. Using 1 layer is cheap and easy. Using 3 layers makes beam very strong but maybe too stiff. More than 3 layers is hard to stick and might peel off fast, so we stop at 3. This range covers most real fixes. Note on Control: were did not make "Control Beam" for 200 kN team. were compare P2 beams to P1 control. This shows total gain from both tighter prestressed strand and sheet together. were admitted this limits saw effect of wire alone, but it showed full effect of upgrading weak beam to super strong one.

Table 3.1: Experimental Program Matrix for Concrete Beams.

Specimen ID	Description	Prestressing Force (kN)	Number of CFRP Layers
PCB-CON	Control Beam (Reference)	150	0
PCB-P1-S1	Strengthened Beam	150	1
PCB-P1-S2	Strengthened Beam	150	2
PCB-P1-S3	Strengthened Beam	150	3
PCB-P2-S1	Strengthened Beam	200	1
PCB-P2-S2	Strengthened Beam	200	2
PCB-P2-S3	Strengthened Beam	200	3

3.2 Trail Mixing:

We made concrete mix to be strong (40 MPa). We used cement, sand, small stones, and water. We added special "superplasticizer" liquid to make wet concrete flow easy without adding too much water.

Table 3.2: Concrete Mix Proportions per Cubic Meter.

Component	Quantity (kg/m ³)
Portland Cement (CEM I)	465
Water	180
Fine Aggregate (Sand)	720
Coarse Aggregate (Gravel)	1050
Superplasticizer	4.5

The beams were reinforced by Two bars (2Ø12 mm) at top and bottom level, to hold stirrups. Was put stirrups every 110 mm to prevent shear cracks. The strand wire (12.7 mm), was pulled using hydraulic machine before pouring concrete (pre-tensioning). Was measured pull force carefully. After concrete got hard, was cut wire ends to squeeze beam.

3.3 CFRP sheet fixing process: Was used CFRP sheets, the sticking it right is key.

Cleaning: We cleaned concrete bottom very well.

Grinding: We used grinder tool to remove dust and weak cement skin until we saw small stones. This makes surface rough so glue holds tight.

Primer: We put thin primer paint to seal concrete.

Gluing: We put epoxy glue layer. We kept it thin (about 1 mm) and even.

Pressing: We pressed cloth onto glue with roller. We pushed out all air bubbles. Air bubbles are bad because they make cloth peel off early.

Beams strengthening with CFRP sheets were left to 7 days before testing to let glue get necessary strength.

3.4 Testing Steps

The beams on were putted on two supports (see Fig. (4.2)). We pressed down at two points in middle. This makes “pure bending” zone in center. Was used universal machine test (500 kN jack) to push slowly (0.5 mm per min). The sensors were putted to measure deflection and strain:

LVDT sensors: Measure how much beam deflection at center.

Strain gauges: Small stickers on concrete and cloth to measure stretch.

Load cell: Measures push force.

The computer recorded all data received from the sensors every second.

3.5 Math and Computer Model

The math rules were used to check if test results make sense. “Nominal Moment” (Mn) was calculated by adding strength of concrete, steel, strand, and CFRP sheets.

$$Mn = Aps * fps * \left(dp - \frac{a}{2}\right) + As * fs * \left(ds - \frac{a}{2}\right) + Afrp * ffe * \left(h - \frac{a}{2}\right)$$

Where A is area, f is stress, and d is depth.

Was also found “Cracking Moment” (Mcr) to know when first crack appears.

$$Mcr = \frac{(fr * Ig)}{yt}$$

Yield Point Definition: It is tricky because cloth does not yield like steel. We define “Yield” as point when steel bar inside reaches 0.002 strain OR when load-deflection curve bends sharply. We calculate Ductility Index (μ) = $\frac{\Delta u}{\Delta y}$ (Final Sag / Yield Sag). If beam breaks early (debonding) before steel yields, we use sag at break point as Δu . This helps us compare brittle beams with ductile ones fairly.

3.6 Computer Model (ABAQUS): We built 3D model in ABAQUS software to validate tests.

Concrete: Modeled as solid blocks with “Damaged Plasticity” rule to show cracks and crush.

Steel/Wire: Modeled as trusses buried in concrete.

CFRP sheets: Modeled as shell layer.

Glue: Modeled as “Cohesive” layer. This is vital, it allows model to simulate sheets peeling off concrete.

4. Results and Discussion

4.1 Results

The results obtained from laboratory tests of the seven girder models will be discussed. The results will be analyzed to understand the behavior of the carbon-reinforced beams.

4.1 Load vs. Bending and Stiffness

The behavior of beams under loading was studied, and it was observed that they progress through three distinct stages before ultimate failure occurs:

Elastic Behavior: Before cracking, the beam remains stiff and deforms as a line proportional to the applied load.

Cracked Stage: Cracks begin to appear in the concrete (at middle part), and the beam deforms more rapidly.

Yield Stage: The steel reinforcement starts to yield, causing significant sagging of the beam.

Failure Stage: The beam can no longer carry additional load, leading to collapse.

Serviceability (Service Stage):

Cracking Load (P_{cr}): Tight strand helps a lot. Beams with 200 kN wire (P2) resisted cracks much better. They held 74 kN load before cracking, while P1 beams cracked at 60 kN. This 24% gain means P2 beams stay solid longer in real life.

Stiffness (K): After cracks appeared, CFRP sheets took over. Beam PCB-P2-S3 (3 layers) was super stiff. It resisted bending twice as hard as control beam. This keeps floors flat in buildings.

Crack Width: Beams with three-layer sheets maintained small-width cracks, while single-layer beams showed wider cracks. Narrow cracks are preferable because they prevent moisture penetration and protect the reinforcing steel from corrosion.

Table 4.1: Bending Behavior Summary.

ID	Wire Pull (kN)	Layers	Crack Load (P _{cr}) [kN]	Yield Load (P _y) [kN]	Max Load (P _u) [kN]	Max Sag (Delta _u) [mm]
PCB-CON	150	0	55.2	165.8	188.5	32.4
PCB-P1-S1	150	1	60.1	210.4	254.5	28.1
PCB-P1-S2	150	2	61.5	235.1	305.2	25.5
PCB-P1-S3	150	3	62.8	248.6	348.7	23.8
PCB-P2-S1	200	1	72.4	238.9	285.3	27.2
PCB-P2-S2	200	2	74.1	260.5	340.8	24.6
PCB-P2-S3	200	3	75.5	275.3	389.1	22.9

4.2 Max Strength and Ductility Analysis

We found big strength gain. Beam PCB-P2-S3 was 106% stronger than control beam. Cloth acts like extra steel muscle. It pulls bottom of beam so it can carry huge weight.

Ductility index (Safety Warning index) (μ).

$$\mu = \frac{\Delta_u}{\Delta_y}$$

: is deflection of beams, when its start yield (permanent stretch). Δ_y

is ultimate deflection of beams. Δ_u

For brittle beams that CFRP sheets peel off early, and defined Δ_u as sag at moment of peeling.

Control Beam: $\mu = 3.15$. It deflection a lot before crushing. This gives warning before fracture.

Strengthened Beams: When added CFRP sheets, beams got more stiff, but brittle behaviour. PCB-P2-S3 had $\mu = 1.74$. It snapped suddenly. This is dangerous. One layer gives good strength (+35%) and keeps safety ($\mu = 2.58$). Three layers give strength (+85%) but in same time low safety.

Table 4.2: Strength Gain and Ductility.

ID	Strength Gain	Yield Deflection Δ_y (mm)	Ductility Index μ	Stiffness After Crack (kN/mm)
PCB-CON	–	10.28	3.15	9.8
PCB-P1-S1	+35.0%	10.90	2.58	13.5
PCB-P1-S2	+61.9%	12.03	2.12	15.8
PCB-P1-S3	+85.0%	12.87	1.85	17.5
PCB-P2-S1	+51.4%	11.53	2.36	14.2
PCB-P2-S2	+80.8%	12.43	1.98	16.9
PCB-P2-S3	+106.4%	13.16	1.74	18.8

4.3 Modes of Failure

Control Beam: The beam failed by yielding of the steel reinforcement first, which represents a classic and safe failure mode. Cracks appeared at the mid-span in the tension zone and propagated upward until failure occurred.

1 Layer (S1): The failure was attributed to matrix cracking and the cutting of carbon fibers. Strain gauges showed that the CFRP sheets reached 91% of their limit. This means that almost the full strength of the sheets was utilized. Efficient, See (Fig. 4.1a).

2 & 3 Layers (S2, S3): Failure occurred due to debonding (peeling) at the adhesive interface between the concrete and the CFRP sheets, or between adjacent CFRP layers.

The Mechanics: When beam bends, cloth wants to stay straight. This pulling force creates shear stress (sliding force) between glue and concrete. With 3 layers, cloth is very stiff and pulls super hard. The shear stress at cracks becomes huge. This leads to the separation of the outer covering of the concrete, see (Fig. 4.1b).

The Result: FRP sheets peels off before it can stretch fully. Strain gauges showed outer FRP only used 55% of fully strength. This is means waste of material, see (Fig. 4.1c).

Effect of Prestressing: When stand tensioned to (200 kN) the cracking were delayed, but once peeling started, it happened faster and more violently than in 150 kN beams.

Table 4.3: Failure Modes and Efficiency.

ID	Mode	Measured Strain	Limit Strain	Efficiency
PCB-CON	Concrete Crush	–	–	–
PCB-P1-S1	FRP Rupture	0.0156	0.017	91.8%
PCB-P1-S2	Peeling Off	0.0108	0.017	63.5%
PCB-P1-S3	Bad Peeling	0.0094	0.017	55.3%
PCB-P2-S1	FRP Rupture	0.0158	0.017	92.9%
PCB-P2-S2	Peeling Off	0.0112	0.017	65.9%
PCB-P2-S3	Bad Peeling	0.0099	0.017	58.2%

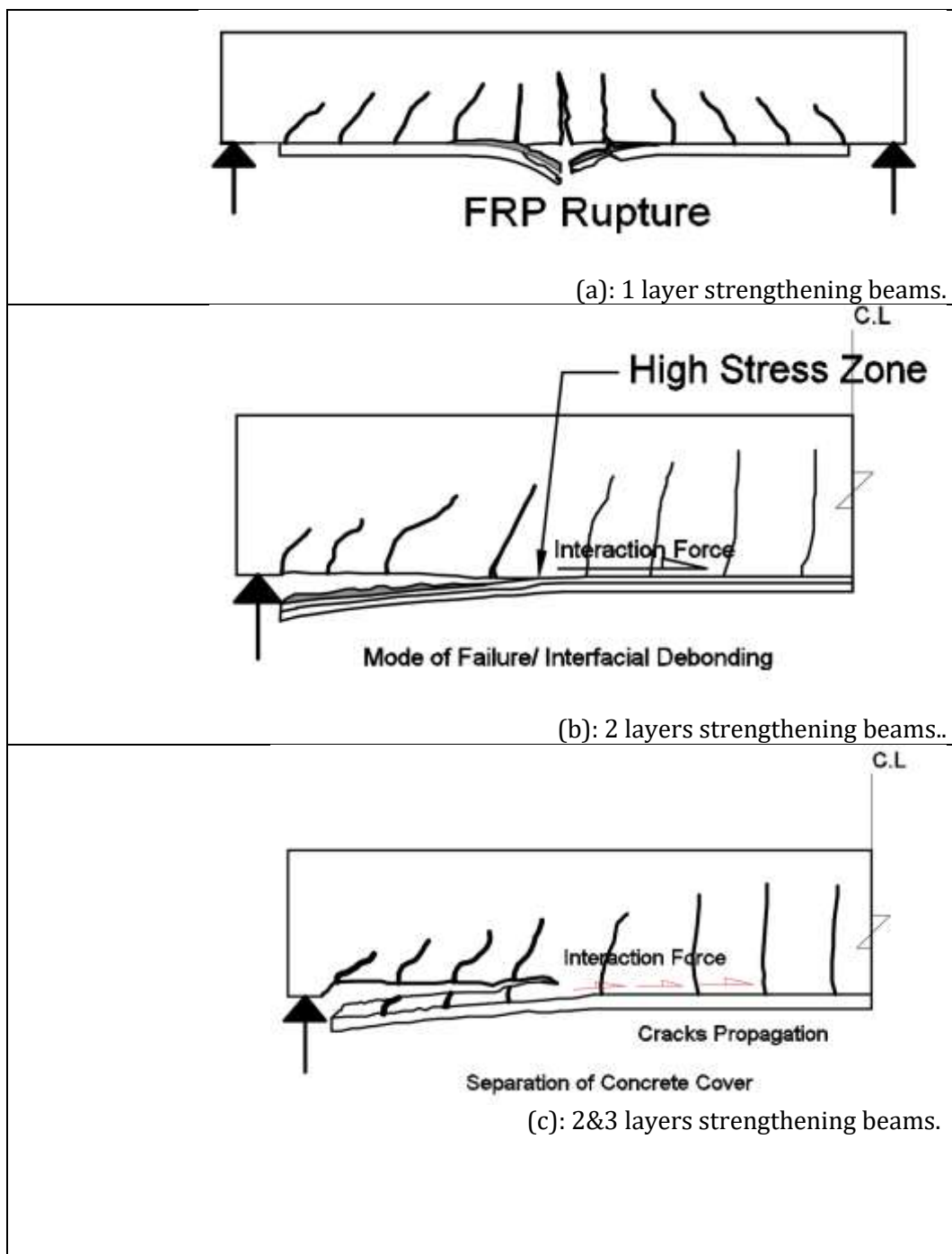


Figure (4.1): Modes of Failure

4.4 Computer Model Validation (FEM)

Curve Matching: We put Test lines and Computer lines on same graph. They overlap almost perfectly for initial stiffness and yield point.

The variation in results: Max load difference was tiny (less than 5% error). Max sag difference was less than 7%.

Failure Pattern: Computer showed red zones (high stress) exactly where real beams peeled off.

Why Valid? Because model predicted both rupture (for S1) and peeling (for S3) correctly without us forcing it. This means math inside model (Cohesive Zone) is right.

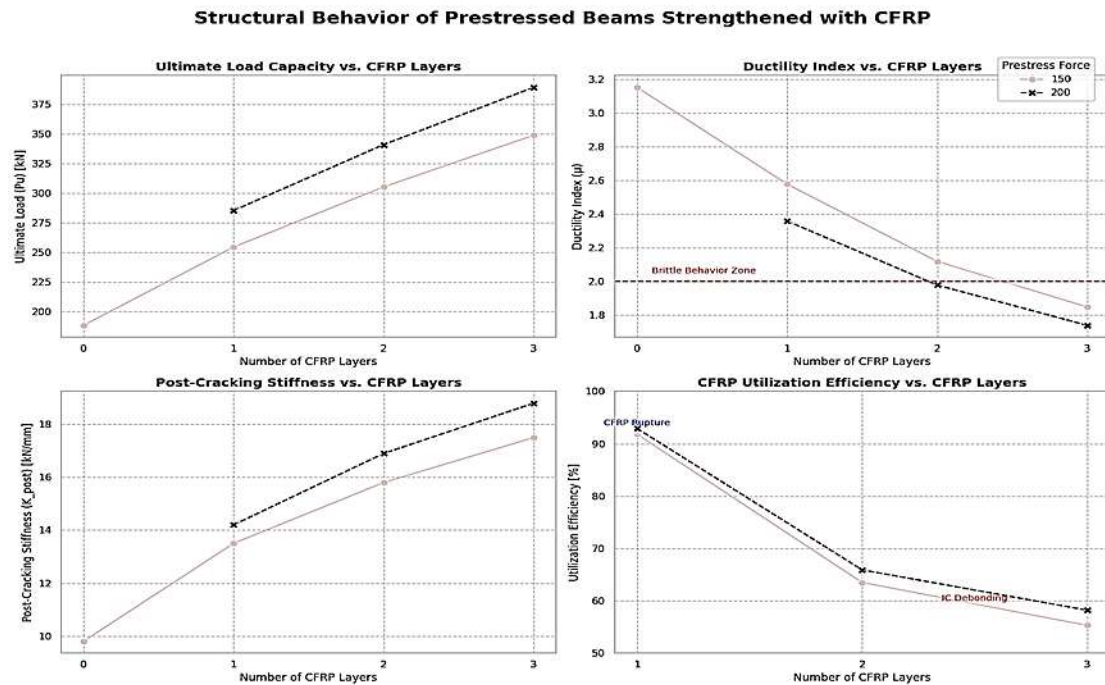


Figure 4.2: Integrated Effects of CFRP Strengthening and Prestressing Force on Beam Structural Behaviour.

Figure 4.2 comprehensively illustrates the interconnected effects of increasing the number of Carbon Fiber Reinforced Polymer (CFRP) layers and the level of prestressing force (150 and 200 kN) on key structural performance indicators.

Figure 4.1 puts it all together.

Top-Left: Shows Max Load going up as layers' increase. P2 line is higher than P1 line.

Top-Right: Shows Ductility falling down fast. It crosses "Red Danger Line" at 2 layers.

Bottom-Right: Shows Efficiency dropping. 1 layer uses 92% of cloth. 3 layers use only 58%.

Conclusion from Figure: Best design is 1 Layer. It gives good strength (+51% with P2) and high efficiency (>90%) and safe ductility. Adding more layers' wastes money and reduces safety.

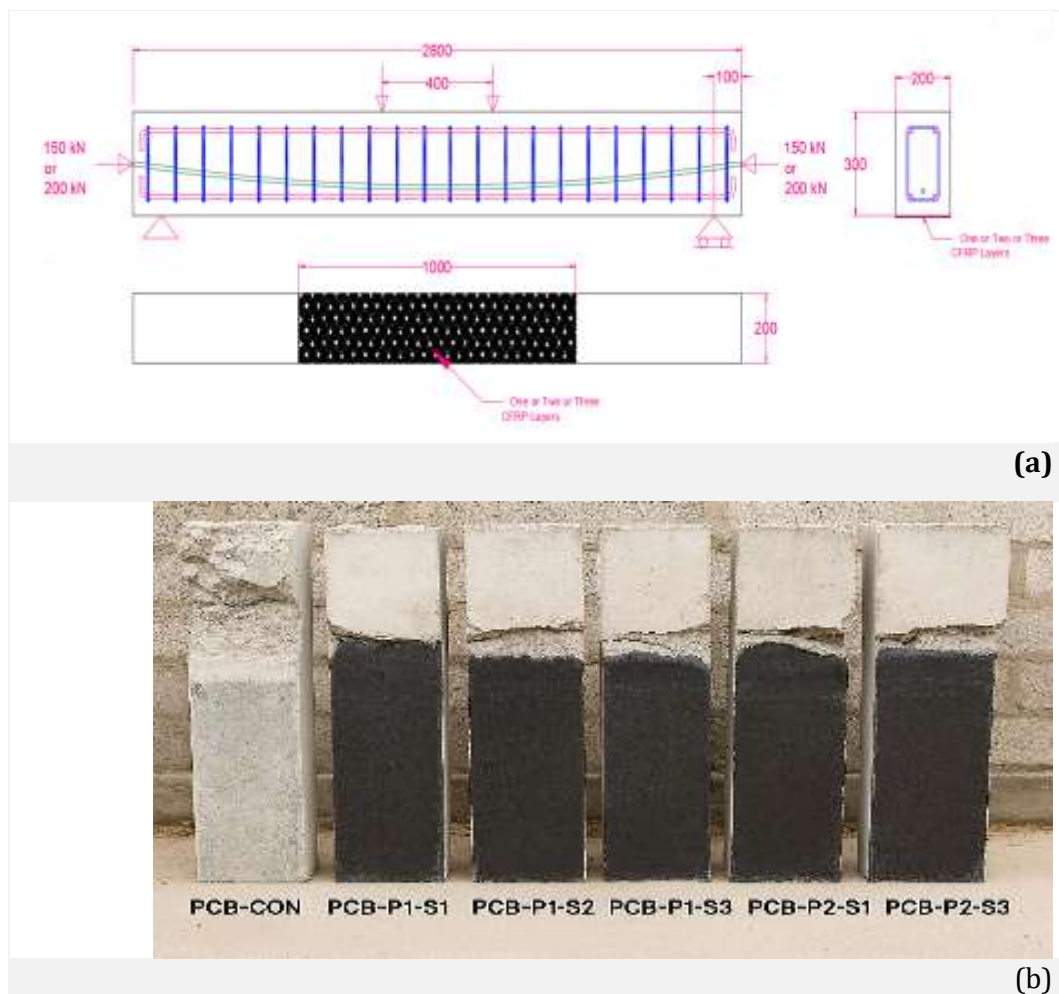


Figure 4.3: (a) The dimensions of experimental prototype showing the Length of CFRP sheet (b) Images of CFRP-Strengthened Concrete Specimens After Final Failure.

These figure 4.3 show real proof of how beams failed.

Control Beam (Left): the mid span of Concrete is cracked in tension zone because the reinforcement steel is yield, this fail mode is safe failure.

1 Layer (S1): The concrete exhibited significant wide cracking, accompanied by matrix breakdown in the CFRP and tearing of some parts from the bottom (since the cloth was not removed). This indicates that the sheets performed as intended.

2 & 3 Layers (S2, S3): CFRP sheets were peeled. This is "Debonding." It happened fast. This matches our low efficiency numbers (only 55% used).

Bottom Line: Photos prove that adding more cloth makes beam stronger but changes failure from safe failure (ductile behaviour) to sudden failure (brittle behaviour).

5. Discussion

It has been shown that CFRP sheets make reinforced beams much stronger, but caution should be exercised in deciding to use multiple layers of CFRP sheets.

5.1 Strength vs. Safety:

Adding CFRP sheets strength beams by 106% (PCB-P2-S3). This matches other studies on normal beams (Alkurdi, 2021). Tightening internal wire also helped stop cracks early, which is good for keeping water out (O'Hegarty et al., 2021). But there is a catch: As strength goes up, safety goes down. Beams with 3 layers became stiff and brittle. They lost (ductility). This is a known problem (Wang et al., 2022), but show it happens because failure mode changes.

1 Layer: FRP breaks. Good use of material.

3 Layers: Sheets peels. Bad use of material.

This peeling happens because stiff cloth pulls too hard on concrete skin (Mazaheripour, 2015). Engineers must know this: More is not always better.

5.2 Practical Advice for Engineers:

Best Choice: Use **1 Layer** of CFRP. It gives good strength gain (+35-51%) and ductile behaviour. It utilizes almost the full strength of the fabric.

Warning: If using 2 or 3 layers, you must use anchors (bolts or wraps) to stop peeling (Noël, 2013). Without anchors, extra layers are waste of money and might be unsafe, because sudden failure.

Design Rule: Use reduction factor (ϕ) in math to account for peeling risk (Huang, 2019).

5.3 Green Building (Sustainability)

Fixing old beams with outer strengthening sheets is better for earth than building new ones. Cloth is light, so trucks use less gas. It stops rust, so repair lasts longer. It saves old concrete from trash.

6. Conclusions

Seven beams with tight wires and sticky cloth were tested, and were used real tests and computer models. Here is what we learned for sure:

Huge Strength: Cloth works. It made beams up to 106% stronger. It also made them twice as stiff, so they do not sag.

Safety Drop (The Danger): Adding cloth cuts ductility in half. Beam changes from "bending a lot" to "snapping sudden." This is because failure shifts from breaking cloth to peeling off concrete.

The Sweet Spot: 1 Layer is winner. It balances added strength with safety. It uses 92% of cloth capacity. 3 layers only use 55% because they peel early.

Tight Wire Helps: Pulling internal wire to 200 kN delayed cracks by 24%. This keeps beam sealed and durable.

Green Choice: Using CFRP is smart for planet. It fixes old structures fast with little waste. It extends life of bridges.

Final Rule: Engineers should fix beams with 1 layer for best result. If more layers are needed, they must fix the peeling problem first (using anchors).

Reference:

- [1] Alkurdi, N. (2021). Flexural behaviour of enhanced foamed concrete beams reinforced with GFRP bars (Master's thesis, Nottingham Trent University). <https://www.researchgate.net/profile/Nadir-Alkurdi>.
- [2] Covatariu, D., Filip, A., & Covatariu, G. (2024). Computational assessment regarding structural rehabilitation of a reinforced concrete decanter tank. *IOP Conference Series: Materials Science and Engineering*, 1304(1), 012018. <https://doi.org/10.1088/1757-899X/1304/1/012018>.
- [3] El Baky, H. A. (2008). Nonlinear micromechanics-based finite element analysis of the interfacial behaviour of FRP-strengthened reinforced concrete beams (Doctoral dissertation, Université de Sherbrooke).
- [4] El Gendy, M., El Arabi, I., Elbarbary, A., & Hamed, M. (2025). Comparative study of structural behaviour of CFRP tubes and traditional steel for pile and column applications, in compliance with international codes. *Discover Civil Engineering*, 2(1), 1–33. <https://doi.org/10.1007/s44290-025-00244-6>.
- [5] Elharouney, B. H., Hussein, A., Mostafa, E. E. D., & Elnemr, A. (2019). Flexural behaviour of prestressed concrete beams strengthened by near-surface-mounted FRP rods. *Journal of Al-Azhar University Engineering Sector*, 14(53), 1424–1435. <https://doi.org/10.21608/AUEJ.2019.64241>.
- [6] Garg, S., Matsagar, V., & Marburg, S. (2023). Nonlinear finite element analyses of prestressed concrete beams strengthened with CFRP laminate. *Structural Engineering International*, 33(2), 258–264. <https://doi.org/10.1080/10168664.2022.2158449>.
- [7] Gupta, C., Arora, H. C., Kumar, A., Kumar, P., Kapoor, N. R., & Sharma, M. (2024). Axial capacity estimation of FRP-strengthened corroded concrete columns. *Journal of Soft Computing in Civil Engineering*, 8(4), 160–185. <https://doi.org/10.22115/scce.2024.414586.1708>.
- [8] Hassas, N., & Bordbar, A. T. (2025). Investigating the problems of historical buildings in relation to earthquakes and researching some of their retrofitting methods. *Budownictwo i Architektura*, 24(1), 75–95. <https://doi.org/10.35784/bud-arch.6519>.
- [9] Hu, Z., Elchalakani, M., Yehia, S., Ran, H., Sadakkathulla, M. A., & Guo, X. (2024). Engineered cementitious composite (ECC) strengthening of reinforced concrete structures: A state-of-the-art review. *Journal of Building Engineering*, 86(1), Article 108941. <https://doi.org/10.1016/j.jobbe.2024.108941>.
- [10] Huang, J. (2019). Structural performance of precast reinforced geopolymer concrete sandwich panels enabled by FRP connectors (Doctoral dissertation, The Hong Kong Polytechnic University). <https://theses.lib.polyu.edu.hk/handle/200/10015>.
- [11] Işıklı, Y. (2025). Strut and tie modelling of reinforced concrete structures with dual-system optimisation. (Doctoral dissertation, Middle East Technical University). <https://open.metu.edu.tr/handle/11511/113997>.
- [12] Jin, L., Li, X., Zhang, R., & Du, X. (2024). Failure mechanism and dynamic response of reinforced concrete joints under impact load acting on beam ends. *International Journal of Impact Engineering*, 185, Article 104863. <https://doi.org/10.1016/j.ijimpeng.2023.104863>.
- [13] Khan, W., Akhtar, S., Rawat, A., & Basu, A. (2024). Experimental and numerical study on flexural behaviour of concrete beams with notch and repairing materials. *Sustainability*, March 2024, 16(7), Article 2723. <https://doi.org/10.3390/su.16072723>.
- [14] Koura, M. M., Tahwia, A. M., & Matthana, M. H. (2024). Influence of macro-synthetic fibres on the flexural behaviour of high-strength concrete beams reinforced with

- GFRP bars. *Mansoura Engineering Journal*, 49(4), 1–12.
<https://doi.org/10.58491/2735-4202.3205>.
- [15] Liu, S., Wang, X., Ali, Y., Huang, H., & Wu, Z. (2024). Evaluation of deflection calculation for hybrid-reinforced concrete with fibre-reinforced polymer and steel bars. *ACI Structural Journal*, 121(4). <https://doi.org/10.14359/51740717>.
- [16] Mansour, W., Osama, B., Li, W., Wang, P., & Sobuz, M. H. R. (2024). Numerical response of concrete-filled steel tubular (CFST) columns externally strengthened with FRP composites subjected to cyclic loading. *International Journal of Concrete Structures and Materials*, 18(1), Article 82. <https://doi.org/10.1186/s40069-024-00716-6>.
- [17] Mazaheripour, H. (2015). Structural behaviour of hybrid GFRP and steel reinforced FRC prestressed beams (Doctoral dissertation, Universidade do Minho). <https://hdl.handle.net/1822/41858>.
- [18] Montaser, W. M., Shaaban, I. G., Zaher, A. H., Khan, S. U., & Sayed, M. N. (2022). Structural behaviour of polystyrene foam lightweight concrete beams strengthened with FRP laminates. *International Journal of Concrete Structures and Materials*, 16(1), Article 59. <https://doi.org/10.1186/s40069-022-0059-x>.
- [19] Näsborn, A., Thoma, K., & Kaufmann, W. (2024). Construction and testing of a CFRP-prestressed railway bridge prototype. *IABSE Symposium Report*, 90–98. <https://doi.org/10.2749/manchester.2024.0090>.
- [20] Noël, M. (2013). Behaviour of post-tensioned slab bridges with FRP reinforcement under monotonic and fatigue loading (Doctoral dissertation, Waterloo University, Canada). <https://hdl.handle.net/10012/647>.
- [21] O'Hegarty, R., Kinnane, O., Grimes, M., Newell, J., Clifford, M., & West, R. (2021). Development of thin precast concrete sandwich panels: Challenges and outcomes. *Construction and Building Materials*, 267, Article 120981. <https://doi.org/10.1016/j.conbuildmat.2020.120981>.
- [22] Sah, T. P., Lacey, A. W., Hao, H., & Chen, W. (2024). Prefabricated concrete sandwich and other lightweight wall panels for sustainable building construction: State-of-the-art review. *Journal of Building Engineering*, 89, Article 109391. <https://doi.org/10.1016/j.jobe.2024.109391>.
- [23] Shi, J., Wang, H., & Cao, X. (2024). Mechanical behaviour and innovative applications of fibre-reinforced cementitious composite and fibre-reinforced polymer in infrastructures. *Buildings*, 14(12), Article 3993. <https://doi.org/10.3390/buildings14123993>.
- [24] Tayfur, S., Alver, N., Türk, E., Menteşoğlu, M., & Ercan, E. (2024). Failure behaviour of CFRP-strengthened reinforced concrete beam-column joints under reversed-cyclic lateral loading: Mechanical and acoustic emission observations. *Structural Engineering International*, 34(1), 141–152. <https://doi.org/10.1080/10168664.2022.2164237>.
- [25] Wang, K. (2025). Study on a comprehensive evaluation and decision-making method for all-composite bridge structure design scheme. *Advances in Mechanical Engineering*, 17(2), 1–13. <https://doi.org/10.1177/16878132251319676>.
- [26] Wang, X., Li, Y., Wu, S., Li, R., Tian, C., Hou, Q., & Long, F. (2022). Seismic performance of a novel partly precast RC shear wall with double precast edge members and a central T-shape CIP member. *Soil Dynamics and Earthquake Engineering*, 162, Article 107481. <https://doi.org/10.1016/j.soildyn.2022.107481>.
- [27] Yuan, X., Gong, Z., Bai, H., Sun, C., & Shi, L. (Dec. 2024). Flexural behavior of concrete members reinforced with carbon-glass fiber composite plate based on mechanical anchoring. *Structural Engineering International*, 35(1), 1–13. <https://doi.org/10.1080/10168664.2024.2425074>.