American Concrete Institute

Investigating the Effects of U-Wrap Anchored Doubly Strengthened Reinforced Concrete Beams with CFRP Sheets

Khalid Al Shboul, Ph.D.
Hayder Rasheed, Ph.D., P.E., F.ACI
Fahed Salahat, Ph.D.

American Concrete Institute

Outline

- Objective
- Introduction
- Experimental Setup
- Results and Discussion
- Conclusions

Objective

Investigate the contribution of the CFRP strengthening on ductility and serviceability when it is used as compression reinforcement

Introduction

- Externally bonded FRP strengthening is widely accepted as the method of choice in upgrading the flexural capacity of concrete beams.
- FRP composites provide stiffness and strength along the fiber direction in tension and compression, and they behave linearly elastic along that direction up to brittle material failure or rupture.

- FRP drawback: Promotes premature failure due to debonding , reduction of the member ductility

- Unidirectional carbon fiber composites possess similar or slightly lower axial compressive strength than their tensile counterpart

Introduction

- ACI 440.2R limits the extreme fiber stress in concrete in compression under service load to 60% of the compressive strength

- Extending the response of strengthened beams through anchorage may limit the upgraded levels due to serviceability

$$f_{c,s} \leq 0.60 f_c' \qquad (10.2.8b)$$

Experimental Setup

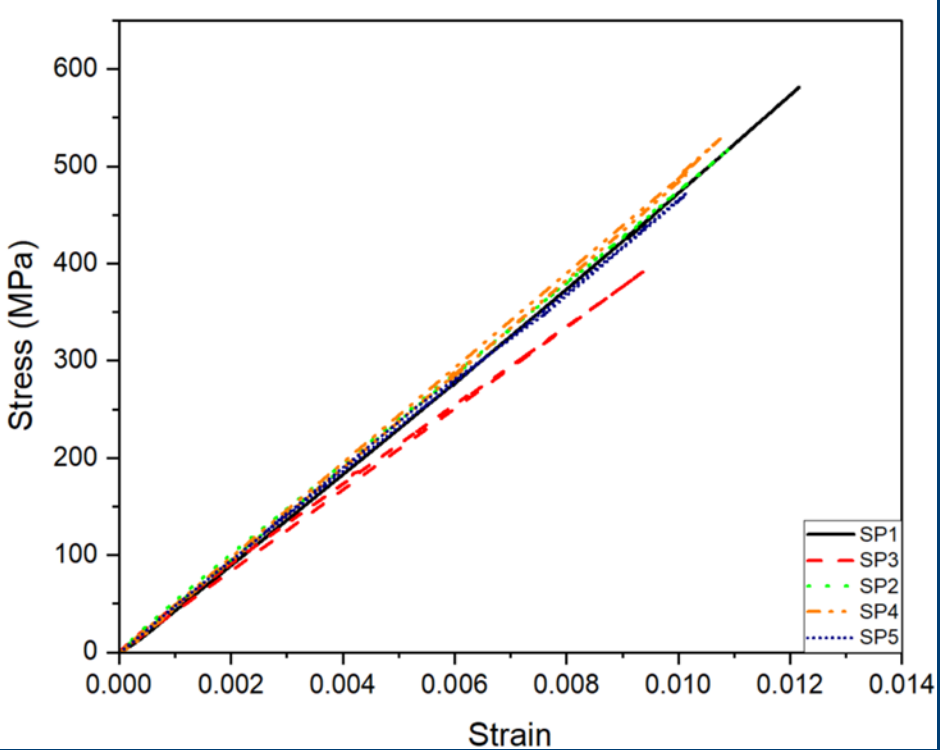
- A total of eight reinforced concrete beams were designed, cast, and tested. All eight specimens were identical in dimensions having the same reinforcement in flexure and shear

- Two deformed rebars Φ 10 mm (2 No. 3) were used as tension reinforcement, and 2 Φ 10 mm (2 No. 3) were used as top reinforcement, stirrups with Φ 10 mm diameter (No. 3) were used and spaced at 57 mm (2.5 in.) center-center along the beam length.

- A normal-weight concrete mixture was used to prepare the material test samples. Compressive strength $f'c$ was determined to be 39.28 MPa **(5.70 ksi)** and 24.18 MPa **(3.51 ksi)** for the normal strength and low strength concrete mixes, respectively.

- Unidirectional high modulus carbon fiber sheets (V-Wrap- C200HM). V-Wrap 770 epoxy resin adhesive material was used

Experimental Setup



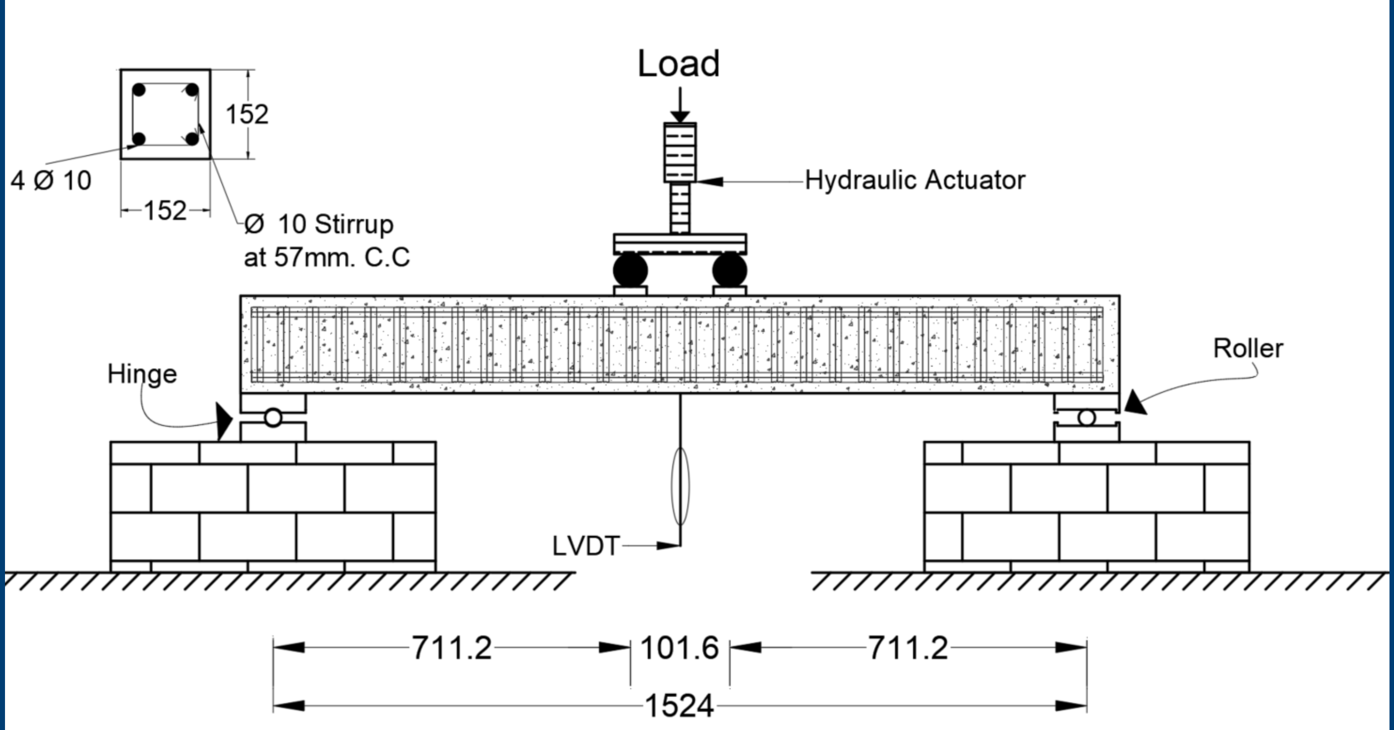
Uniaxial tensile stress-strain test results for High Modulus Carbon Fiber Laminates

Experimental Setup

Test specimens and parameters

Beam	Tension CFRP/No. Layers	Compression CFRP/No. Layers	Notes
B1A	NO	NO	Control/Un-strengthened
B1B	NO	NO	Control/Un-strengthened
B2	YES/1	NO	Control/strengthened
B3	YES/1	YES/2	No U-Wrap anchors
B4	YES/1	YES/2	3 Single U-Wrap anchors per shear span
B5	YES/1	YES/2	3 Double U-Wrap anchors per shear span
B6	YES/1	YES/2	3 Double U-Wrap anchors per shear span with lower strength mix of 24.18 MPa
B7	YES/1	NO	3 Single U-Wrap anchors per shear span

Experimental Setup



Beam details and testing setup (all dimensions are in mm)

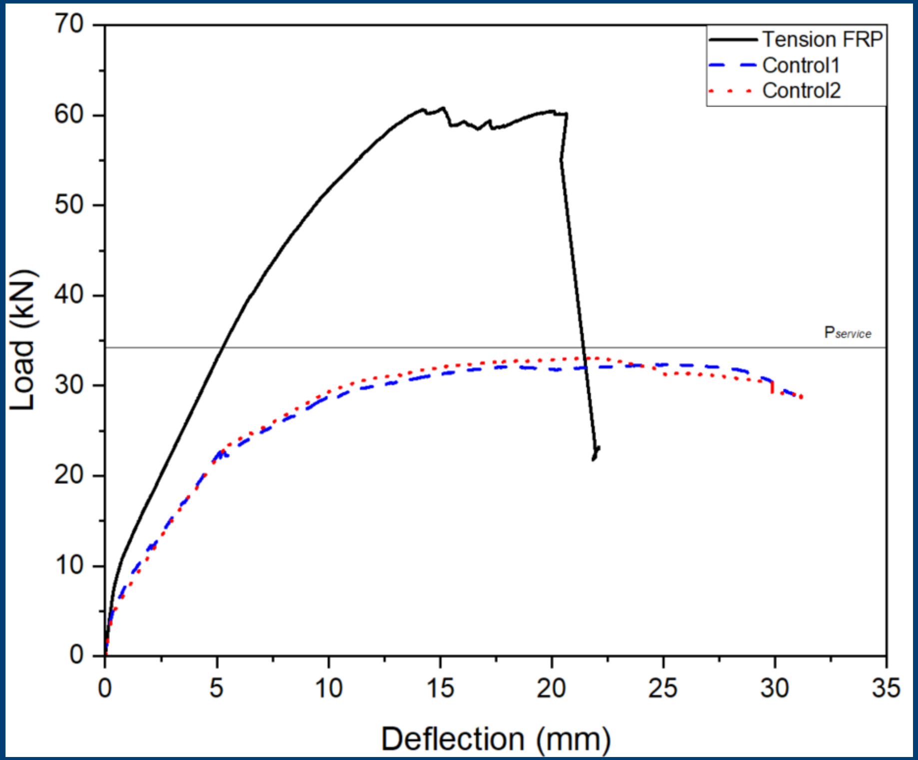
Results and Discussion

Control Beam

- B1A and B1B (un-strengthened control beams) show a typical failure mode of steel yielding followed by concrete crushing at an ultimate load of 33.1 kN (7.44 kips) and 32.93 kN (7.4 kips), respectively

- Beam B2 underwent yielding of steel prior to its final failure by an intermediate crack (IC) debonding,

- The ultimate load carrying capacity of the strengthened beam is significantly higher than that of the control beam, with a maximum load of 60.9 kN (13.68 kips) compared to 32.93 kN (7.4 kips) for the bear control beam. This represents an 86% increase in load carrying capacity,



Experimental Load-deflection curves for the 3 control beams.

Results and Discussion

Control Beam

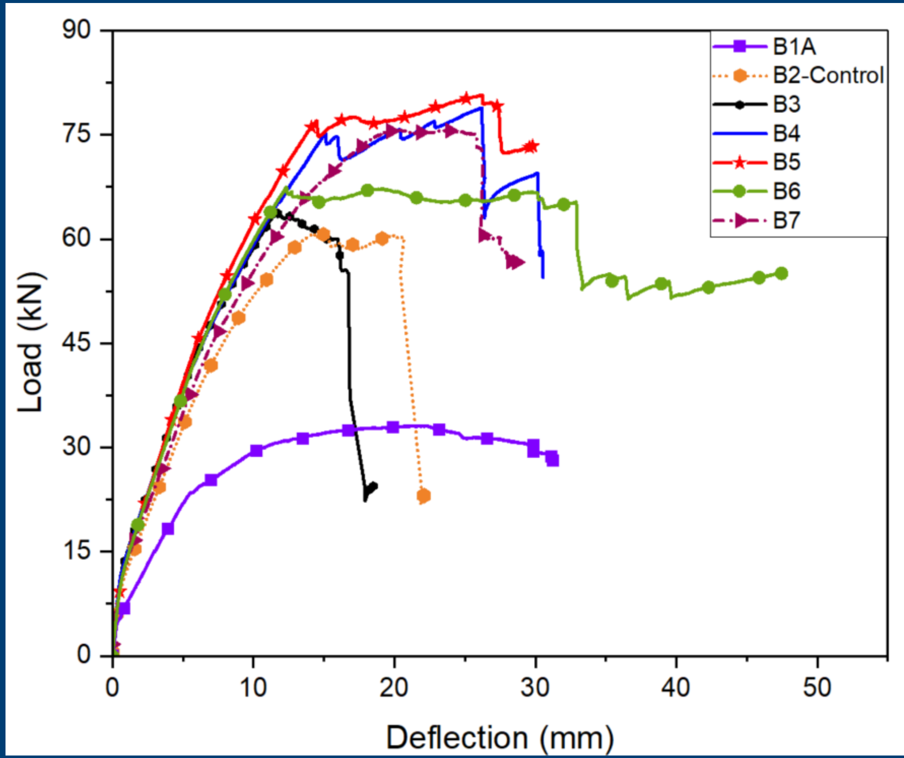
- The strain analysis at the service load level indicates that the stress in the concrete for the strengthened beam is 26.6 MPa (3.85 ksi), which is 12% higher than the stress limit of 0.6f’c specified in the ACI 440.2R guide (ACI 440.2R-17).
- Adding additional layers of strengthening may result in even higher stresses in the concrete extreme fiber, potentially leading to a violation of serviceability limit requirements

Beam 1 after testing (b) Beam2 after testing – Intermediate crack debonding failure mode

Results and Discussion

Doubly reinforced beams with High Modulus CFRP sheets

- B3 has two layers of C200HM in compression with no anchorage
- B4 has two layers of C200HM in compression with a single-layer of U-Wraps spaced at 177.8 mm (7 in.) along each shear span
- B5 has two layers of C200HM in compression with two –layers of U-Wraps spaced at 177.8 mm (7 in.) along each shear span
- The doubly strengthened beams have almost identical but larger post-cracking stiffness compared to Beam B2 and a higher load capacity compared to the singly strengthened control beam.



Load-Deflection curves for the doubly strengthened beams compared to the control strengthened beam.

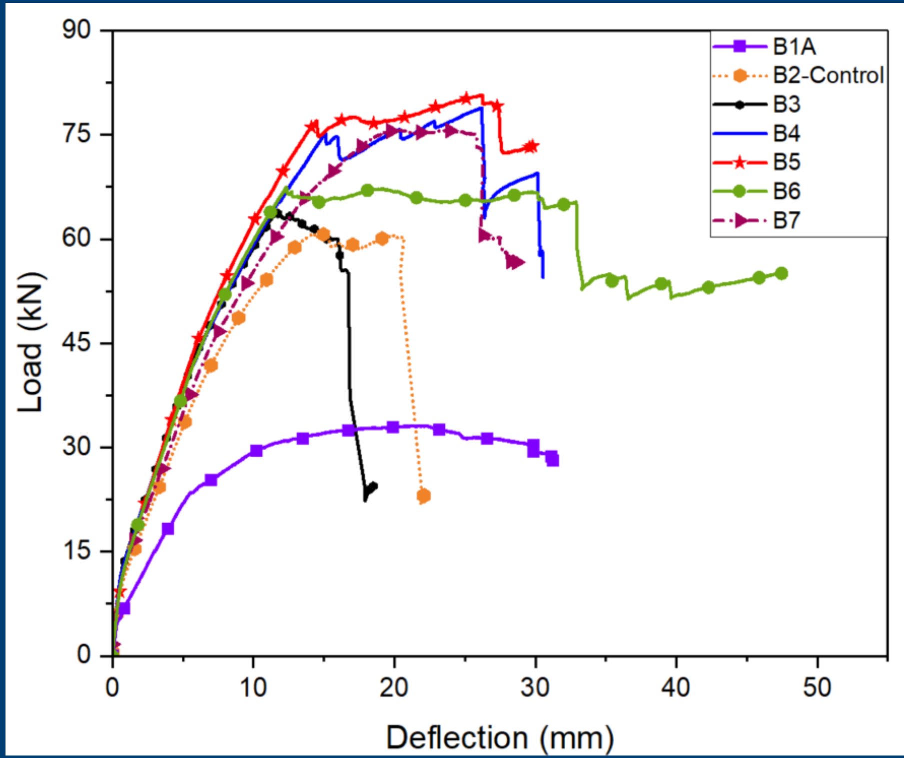
Results and Discussion

Doubly reinforced beams with High Modulus CFRP sheets

- The beam anchored with two layers of U-Wraps shows higher post yielding stiffness while the other beams retain the same behavior up to their ultimate failure

- The ductility increase was noticed in the anchored doubly strengthened beams only. No increase in the ductility was observed in the un-anchored doubly strengthened beam

- The un-anchored doubly strengthened beam (Beam B3) showed the least percent increase in the ultimate loading capacity of about 4.6% compared to the control strengthened beam B2 with a failure load of 63.72 kN (14.32 kips) and ultimate deflection of 18.5 mm (0.72 in).



Load-Deflection curves for the doubly strengthened beams compared to the control strengthened beam.

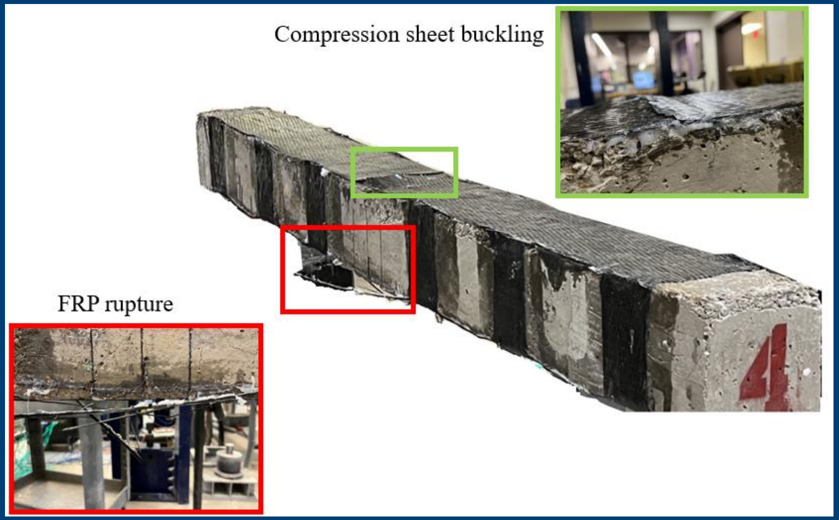
Results and Discussion

Doubly reinforced beams with High Modulus CFRP sheets

- Beams B4 and B5 showed 29.6% and 32.7% increase in the ultimate load capacity, respectively, relative to the control strengthened beam B2.

- The percent increase in the ultimate deflection was 20.6 % and 34.5% for beam B4 and beam B5, respectively, indicating a more ductile behavior observed in the presence of the compression layers and U-Wrap anchors.

- The presence of the U-Wrap anchor shifts the failure mode from sheet debonding to FRP rupture combined with compression sheet buckling in the constant moment region,



Beam B4 and B5 after testing

Results and Discussion

Strain Analysis

The service load was approximated by using the following equation:

$$M_{service} = \frac{\emptyset M_n}{L.F} \qquad \text{Eq. \#1}$$

Hognestad's parabola was used to calculate the stress in the concrete at the service levels using the following formula:

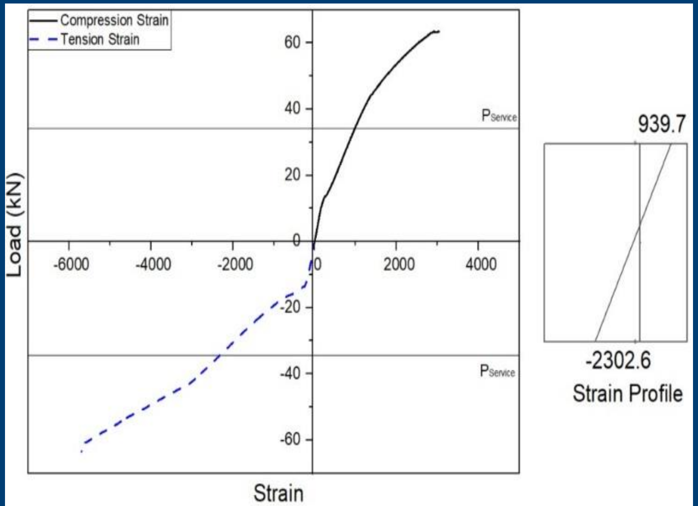
$$\sigma_c = f'_c\left[2\frac{\varepsilon_c}{\varepsilon'_c} - \left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^2\right], 0 < \varepsilon_c < 0.003 \qquad \text{Eq. \#2}$$

$$\varepsilon'_c = 1.71\frac{f'_c}{E_c} \qquad \text{Eq. \#3}$$

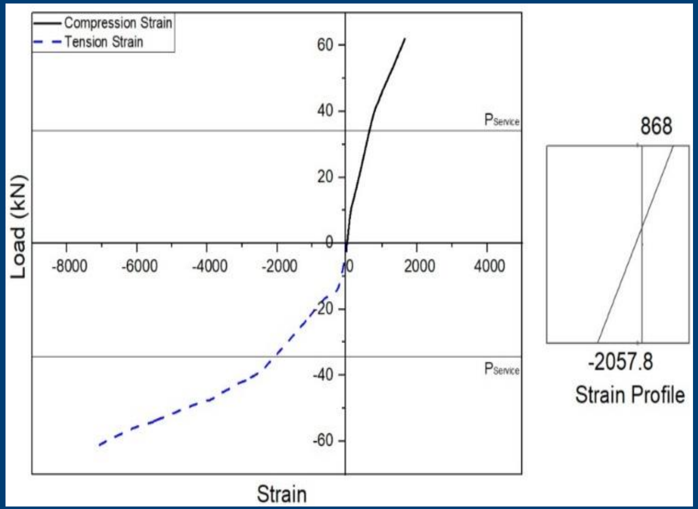
The compression and tension strains were measured at the top and bottom surfaces of the FRP sheets, respectively, both throughout the loading range.

Results and Discussion

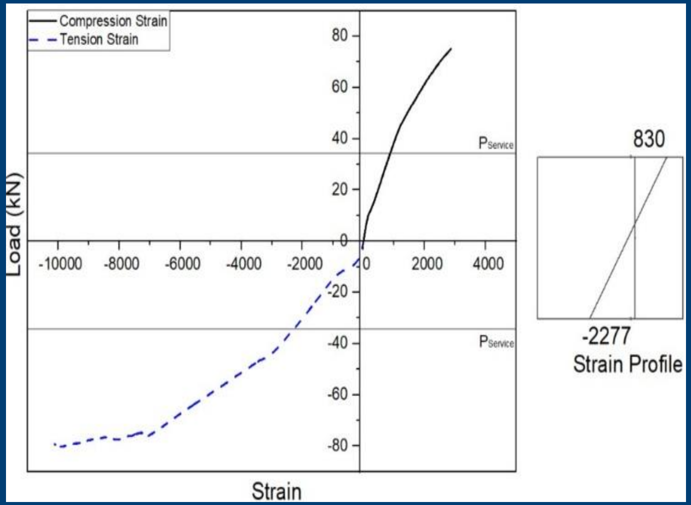
Strain Analysis



a



b



c

(a) B3 Strain profile (b) B4 Strain profile (c) B5 Strain profile

Beam	Concrete stress (Mpa)	$0.6f'_c$	Percent reduction over the control beam
B2(Control)	3.85	3.41	*****
B3	3.74	3.41	3 %
B4	3.53	3.41	8%
B5	3.41	3.41	11%

Critical stress comparison.

Results and Discussion

Doubly reinforced beams with High Modulus CFRP sheets

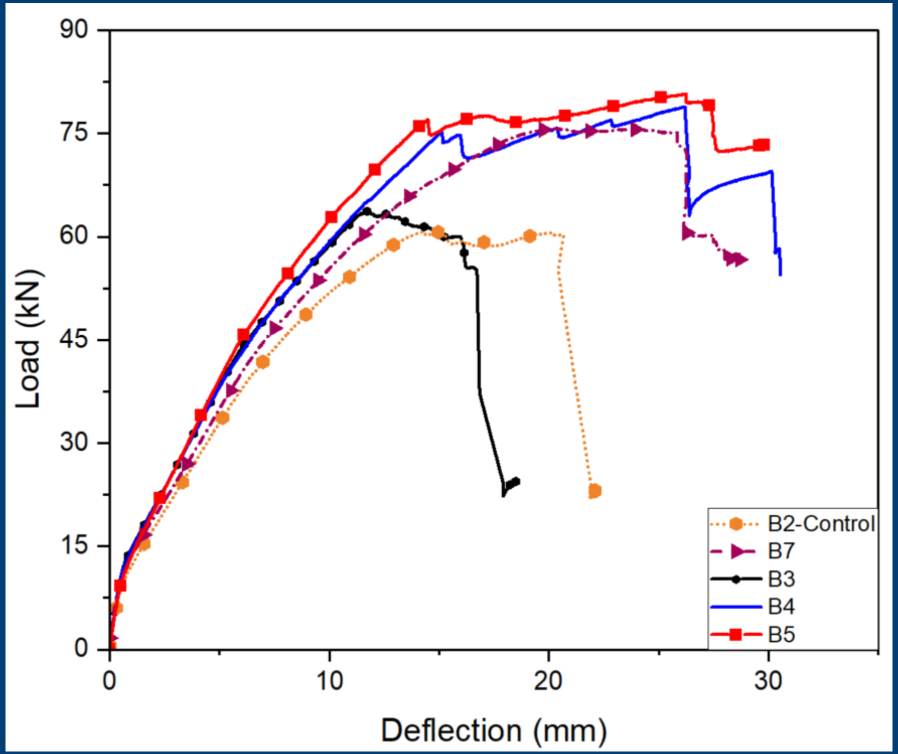
- The addition of the compression layers alone, without anchoring the tension sheets, did not provide significant reduction in the concrete service compressive stress.
- This negligible benefit can be attributed to the IC debonding of the tensile sheet, preventing full utilization of the composite action between the FRP sheet and the concrete.
- Anchoring the tension sheet with a single-layer of U-Wraps effectively improved the transfer of stresses between the CFRP compression sheets and the concrete, leading to a more efficient stress distribution at higher ultimate load.
- Compression FRP sheets bridges the crushed compression zone redistributing the compressive stresses over a wider region even if this layer buckles outwards.

Results and Discussion

Impact of the compression FRP Layers on the behavior

- Comparing the load-deflection curves of beams B2 and B7 (without compression layers) that the implementation of single U-wrap anchors significantly improves the strength by changing the failure mode from IC debonding to CFRP rupture, while they have a minor influence on improving the post-cracking stiffness.

- The ductility ratio is enhanced due to using U-wrap anchors, but the serviceability is caused to suffer since the strength is increased admitting higher compressive concrete stresses at the extreme fiber under the service load. Similar conclusions may be drawn when comparing beams B3 and B4/B5.

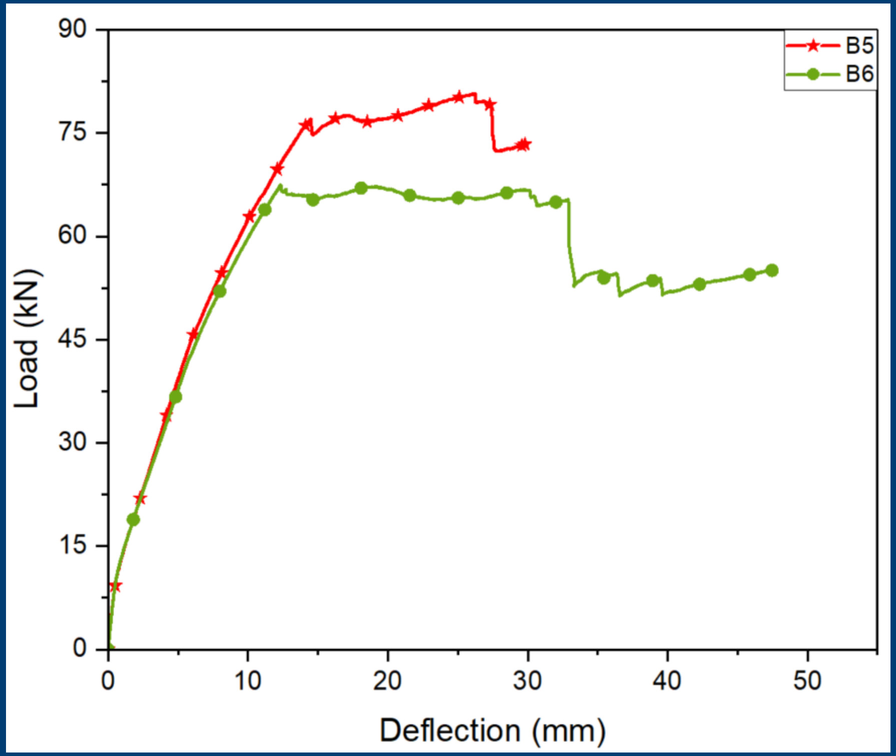


load deflection curves to highlight effect of compression FRP as well as U-Wrap anchorage

Results and Discussion

Impact of the compression FRP Layers on the behavior

- It is expected to see a significant increase in the beam strength in the case of beam B5 having the higher compressive strength due to the delay in attaining concrete crushing and compression FRP layer buckling at the ultimate loading stage.
- Beam B6 exhibited a much higher ductility due to the re-distribution of the stresses in the presence of the compression FRP layers.
- Beam B6 benefits noticeably from the compression FRP layers with respect to serviceability due to its lower compressive strength, thus only allowing lower service compression limit stress. These findings demonstrate the potential of compression FRP layers as a viable solution for strengthening and improving the ductility and serviceability behavior of deficient concrete material strength levels.



Load deflection curves to highlight the effect of the concrete strength on the response of the beams.

Conclusions

- The inclusion of FRP layers, both in tension and compression zones in the presence of U-wrap anchors, has demonstrated significant improvements in load-carrying capacity, stiffness, ductility and serviceability.
- The comparison of the doubly strengthened beams with the singly strengthened control beam highlighted the advantages of the new strengthened configuration.
- The doubly strengthened beams exhibited larger post-cracking stiffness and load capacity, indicating the enhanced structural performance.
- The anchoring of tension layers in the presence of compression layers played a crucial role in shifting the failure mode from intermediate crack debonding to FRP rupture.
- This anchoring technique contributed to a more ductile behavior and increased the ultimate flexural capacity of the beams. The beams anchored with U-Wraps demonstrated superior performance, showcasing significant increases in ultimate load capacity and ductility.
- The utilization of compression FRP layers effectively distributed and transferred compressive forces within the concrete, resulting in an improved stress distribution and reduced concrete compressive stresses.

Conclusions

- The addition of compression layers, when combined with anchoring the tension layer, showed a notable reduction in compressive concrete stress.
- In the case of low strength concrete beams, the new strengthening strategy involving compression FRP layers and double layers of U-Wrap anchorage proved to be highly effective in extending the improvements in behavior.
- These enhancements led to increased load-carrying capacity, post-cracking stiffness, ductility and serviceability of the deficient beams. The distribution and transfer of compressive stresses through the compressive FRP layers successfully mitigated the limitations of low strength concrete, resulting in significant improvements in behavior and performance.
- The experimental findings support the viability of compression FRP layers as a plausible solution for enhancing the behavior of deficient concrete structures. The use of this new FRP strengthening system and U-wrap anchoring technique, offer a promising approach to address structural deficiencies at service levels and improve the ductility of reinforced concrete beams.

Thank you