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Influence of CFRP Thickness, Concrete Strength, and Reinforcement Detailing on the Cyclic Performance of RC Beams

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Abstract - CFRP sheet strengthening has been widely adopted as an effective technique for enhancing the cyclic performance of reinforced concrete (RC) structures. However, variations in CFRP thickness, concrete strength, and steel reinforcement detailing can significantly influence the ductility and energy dissipation of strengthened beams. This study investigates the cyclic response of six full-scale rectangular RC beams subjected to four-point bending flexurally strengthened with CFRP sheet. The beams are categorized into two groups, each consisting of three specimens: a control beam, a beam strengthened with a thin CFRP sheet, and a beam strengthened with a thick CFRP sheet. Group I beams are constructed with No. 13 longitudinal steel and concrete compressive strength of 17.2 MPa, while Group II beams utilize No. 16 longitudinal steel and a higher concrete compressive strength of 31 MPa. Key parameters, including load-deflection behavior, energy dissipation, and ductility, are compared across the two groups. Experimental results highlight the impact of CFRP thickness, concrete strength, and steel reinforcement on RC beam cyclic behavior. Experimental results show that thin CFRP sheets offer a better balance between strength and ductility, enabling higher energy dissipation. Conversely, thick CFRP sheets increase load capacity but reduce ductility due to early debonding. Beams with lower-strength concrete and smaller reinforcement exhibited greater ductility and energy absorption, while higher-strength concrete and larger reinforcement enhanced stiffness and ultimate load capacity.

***Keywords*: Flexural members; Seismic performance; CFRP strengthening; Cyclic response; Energy dissipation**

1. Introduction

The behavior of reinforced concrete (RC) structures strengthened with carbon fiber reinforced polymer (CFRP) under reversed cyclic loading has received limited research attention. Most studies have focused on the monotonic behavior of CFRP-strengthened RC members [1-7], despite the importance of understanding their seismic performance, as cyclic loading, such as that induced by earthquakes, can significantly impact structural resilience. CFRP is widely recognized for its high strength-to-weight ratio, corrosion resistance, and ease of installation [8-12], making it an attractive solution for retrofitting RC structures. However, further research is needed to optimize anchoring methods and improve cyclic behavior.

Research has demonstrated that CFRP improves the strength, ductility, and energy dissipation of RC members like beam-column joints, shear walls, and columns [13-20]. Ceroni [17] reported that using Near Surface Mounted (NSM) bars rather than Externally Bonded Reinforcement (EBR) enhanced ductility and shifted failure modes from debonding to concrete crushing. Other studies, such as those by Laseima et al. [18], Saqan et al. [19], and Karayannis and Golias [20], further demonstrated significant improvements in cyclic behavior when mechanical anchoring systems were used.

This study investigates the cyclic performance of full-scale RC beams strengthened with CFRP sheets of varying thicknesses. Six rectangular beams are divided into two groups based on steel reinforcement detailing and concrete strength: Group I beams, with No. 4 longitudinal steel and 17.2 MPa concrete, and Group II beams, with No. 5 longitudinal steel and 31 MPa concrete. Each group consists of a control beam, a beam strengthened with a thin CFRP sheet, and a beam strengthened with a thick CFRP sheet. The experimental program evaluates key parameters, including load-deflection behavior, energy dissipation, and ductility, to assess the influence of CFRP thickness, concrete strength, and reinforcement detailing on cyclic behavior. Findings aim to provide valuable insights into optimizing CFRP strengthening strategies for enhanced seismic resilience of RC beams.

2. Experimental Campaign

2.1. Specimen Matrix and Beam Parameters

Six full-scale rectangular RC beams were designed and constructed according to the ACI 318 building code [21]. All specimens have identical geometry but differ in terms of longitudinal steel size and concrete compressive strength. Three beams were reinforced with 4 No.13 bars and cast with a concrete compressive strength of 17.2 MPa, while the other three beams were reinforced with 4 No. 16 bars and a concrete compressive strength of 31 MPa. Figures 1 to 3 illustrate the geometry of the tested beams, No.1 to No.6, respectively.

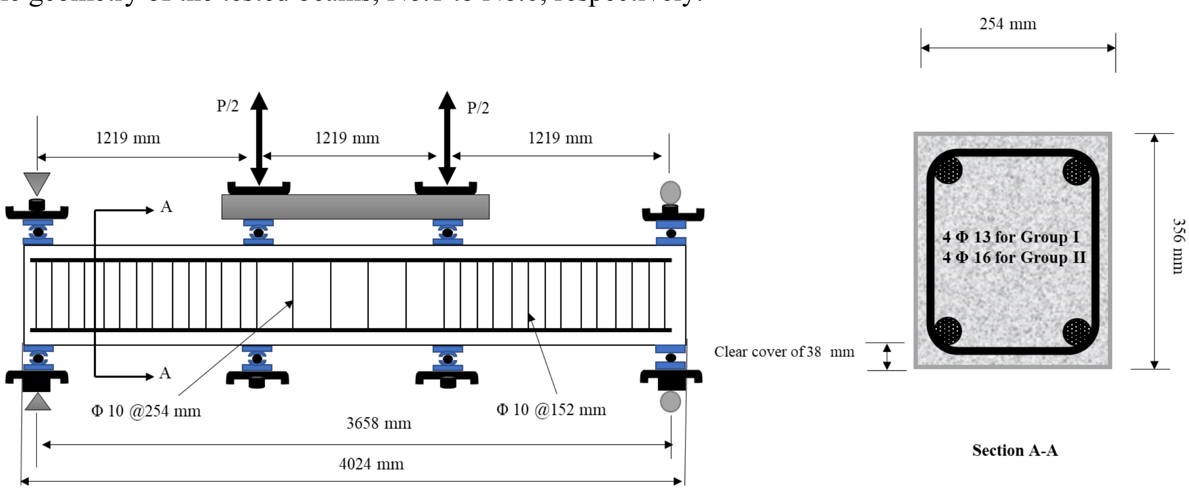

Fig. 1: Beam No.1 and No.4 (Control beams)

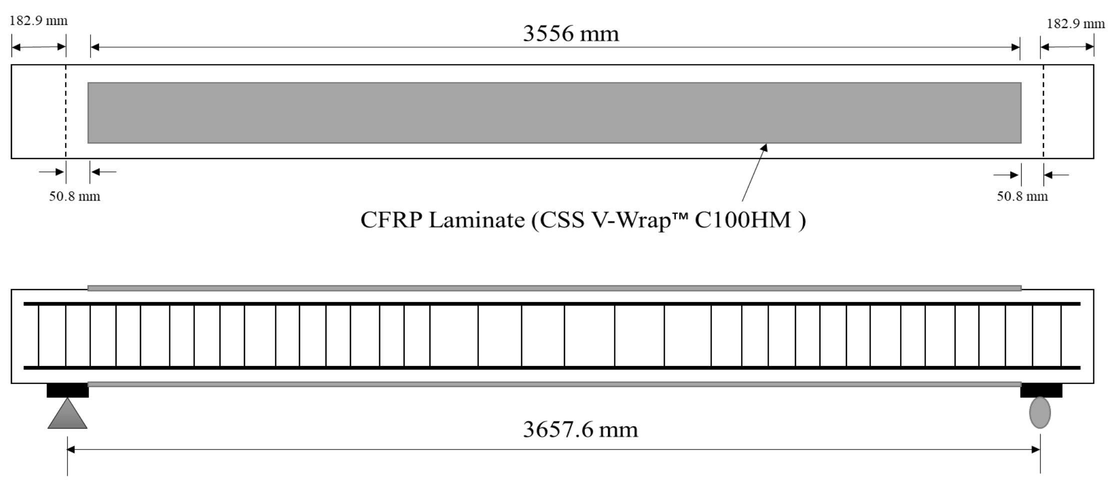

Fig. 2: Beam No.2 and No.5

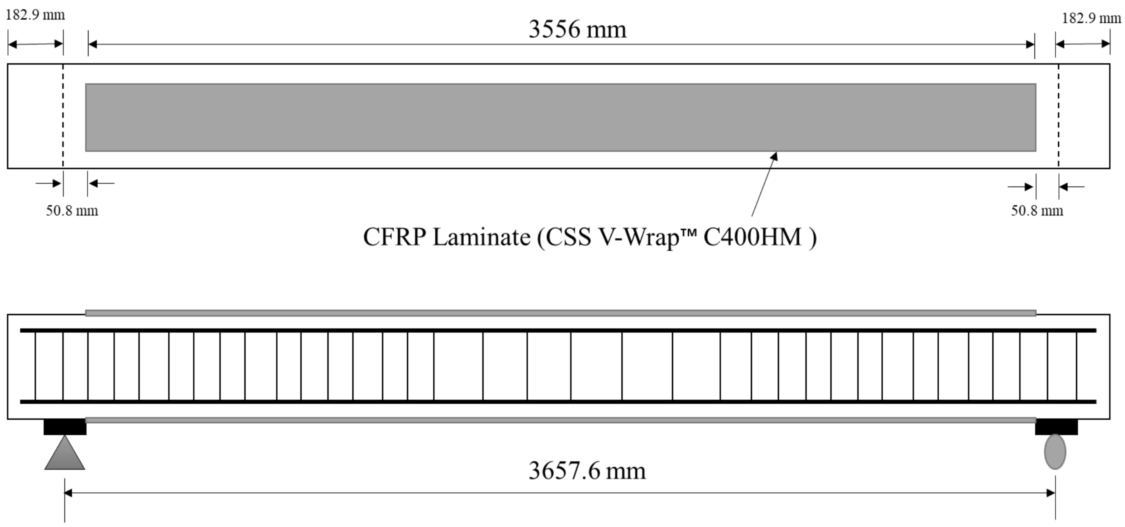

Fig. 3: Beam N.3 and No.6

2.1. Materials Properties

Two different concrete mixes, each with distinct strengths, were used for the tested beams. Group I was designed to achieve a 28-day compressive strength of 17.2 MPa, while Group II was designed for 31 MPa. Concrete cylinder tests conducted according to ASTM C39 showed average strengths of 21 MPa for Group I and 39.28 MPa for Group II. During beam testing, beam No.3 reached a compressive strength of 25.77 MPa, and beam No.5 attained 37.95 MPa.

The main steel reinforcement as well as transverse steel were tested in accordance with ASTM A615. An average yield strength of 485.50 MPa, slightly above the manufacturer specification of 470.20 MPa was reported for the stirrup steel. Regarding the longitudinal steel, the rebars No.13 and No.16 showed average yield strengths of 536.01 MPa and 560.50 MPa, respectively.

Two types of high-modulus unidirectional carbon fiber fabric were used to enhance the flexural capacity of four beams. One fabric, CSS V-Wrap™ C400HM, has a dry thickness of 0.7 mm and a cured ultimate tensile strength of 1241 MPa. The other fabric, CSS V-Wrap™ C100HM, has a dry thickness of 0.17 mm and a cured ultimate tensile strength of 1490 MPa.

2.2. Flexural Strengthening Procedure

The surfaces of the strengthened specimens were prepared after the curing of the concrete mixture using suitable tools to ensure high quality bonding between the CFRP sheets and concrete substrate. Two types of CFRP sheets were involved with different thickness. Table 1 shows the strengthening details of the strengthened beams.

Table 1: strengthening categories of the tested specimens.

Group No	Beam No	Specimen Type	CFRP Sheets	Number of layers
I	1	Control	N/A	N/A
	2	Strengthened with thin sheet	CSS V-Wrap™ C100HM	1 top and bottom
	3	Strengthened with thick sheet	CSS V-Wrap™ C400HM	1 top and bottom
II	4	Control	N/A	N/A
	5	Strengthened with thin sheet	CSS V-Wrap™ C100HM	1 top and bottom
	6	Strengthened with thick sheet	CSS V-Wrap™ C400HM	1 top and bottom

2.3. Loading Protocol and Testing Setup

The seismic load was simulated using a displacement-controlled cyclic four-point loading setup with a 668 kN actuator. The applied displacement rate was 17.78 mm/min, and various instruments, including four LVDTs, strain and an 890 kN load cell, were employed to capture beam behavior. Data was collected using a Vishay System 7000 with multiple channels for strain, displacement, and load. Testing followed AC 125 guidelines, utilizing a simply supported with a 3658 mm clear span and loads applied at one-third points via a steel spreader beam. Steel C channels with pre-tensioned threaded rods provided clamping during pull loading, with each rod handling a maximum force of 133.44 kN under ultimate load, ensuring a safety factor of 1.57. Figure 4 demonstrates the displacement-controlled loading protocol of beam No.2 in accordance with AC 125 [22].

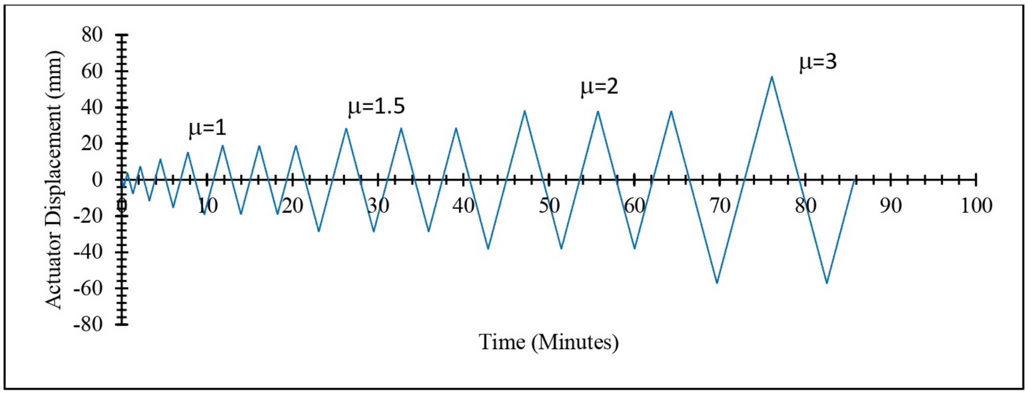

Fig. 4: Loading Protocol of Beam No.2

3. Results and Discussion

The following sections will discuss the results, observations and the finding of the experimental tests for each group.

3.1. Group I

The control specimen (beam No.1) exhibited ductile behavior, withstanding displacements up to 82.55 mm with negligible strength reduction. Cracking occurred at 34.75 kN in the push direction (cycle size 7.62 mm) and 43.14 kN in the pull direction at the same cycle size. Yielding loads were 62.27 kN (push) and 74.59 kN (pull) at a cycle size of 19.05 mm, accompanied by flexural and shear crack propagation. Ultimate failure occurred at 89.01 kN in push (cycle size 82.55 mm) and 125.80 kN in pull. Higher pull-direction loads were attributed to gravity and pin-pin boundary conditions, see Figure 5 for load-displacement of beam No.1.

The second specimen (beam No.2), strengthened with thin CFRP sheets, showed some ductility, sustaining displacements up to 34.30 mm before CFRP rupture. Cracking loads were 34.33 kN (push) and 37.68 kN (pull) with a cycle size of 7.62 mm. Yielding occurred at 80.40 kN (push) and 81.43 kN (pull) at 19.07 mm cycle size, followed by flexural and shear crack development. Failure due to CFRP rupture occurred at 104.80 kN (push) and 124.00 kN (pull) with a displacement of 57.2 mm, caused by large diagonal shear cracks.

The third specimen (beam No. 4), strengthened with thicker CFRP sheets, exhibited reduced ductility, failing at a displacement of 40.64 mm due to CFRP debonding. Cracking loads were 35.30 kN (push) and 32.97 kN (pull) at 3.81 mm cycle size, while yielding occurred at 115.91 kN (push) and 112.73 kN (pull) at 20.32 mm cycle size. Failure loads were 146.34 kN (push) and 154.05 kN (pull), primarily caused by large diagonal shear cracks near load application points. Figure 5 demonstrates the cyclic response of all specimens of group I.

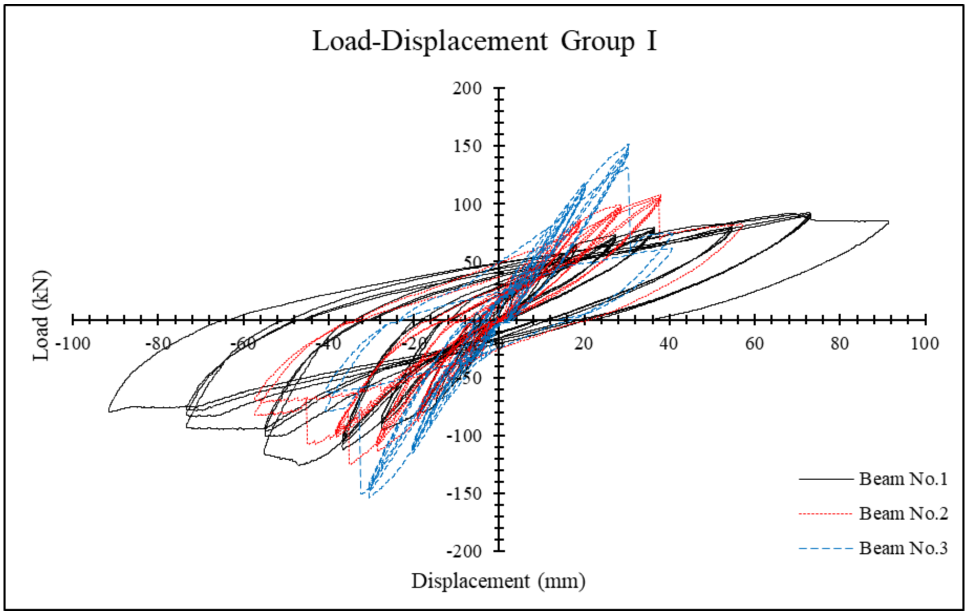

Fig. 5: Load-Displacement response of group I

3.2. Group II

The control beam exhibited a ductile response with significant energy dissipation in hysteresis loops, enduring displacements exceeding 57.15 mm with minimal strength reduction near failure. Initial cracking loads were 34.78 kN (push) and 34.91 kN (pull) at a displacement cycle of 7.62 mm. Yielding occurred at 92.62 kN (push) and 90.55 kN (pull) at 19.05 mm displacement, with additional flexural and shear cracks forming as cycles progressed. Ultimate failure, due to excessive yielding, occurred at 103.20 kN (push) and 107.14 kN (pull) at a displacement cycle of 57.15 mm.

The second specimen, strengthened with thin CFRP sheets, demonstrated some ductility, sustaining displacements of 47.75 mm before CFRP rupture on the top face and 38.11 mm in push due to debonding on the bottom side. Cracking loads were 53.06 kN (push) and 30.87 kN (pull) at 3.81 mm displacement. Yielding occurred at 108.21 kN (push) and 106.80 kN (pull) at a cycle of 29.21 mm. Failure, caused by CFRP rupture and debonding near the shear span, occurred at 136.11 kN (push) and 132.11 kN (pull) at 57.2 mm displacement, attributed to diagonal shear cracks near load points.

Beam BS-C8-NA, strengthened with thicker CFRP sheets, showed reduced ductility, reaching only 30.00 mm displacement at maximum load, a 43% reduction compared to BS-C2-NA. Cracking loads were 52.94 kN (push) and 32.18 kN (pull) at 3.81 mm and 7.62 mm displacements, respectively. Yielding loads were 133.35 kN (push) and 127.67 kN (pull) at 29.21 mm displacement. Failure, caused by CFRP debonding at the shear span, occurred at 173.79 kN (push) and 177.41 kN (pull) at 38.10 mm displacement, with narrower cracks due to increased CFRP restraint. Figure 6 below shows the cyclic response of all beams of group II until failure.

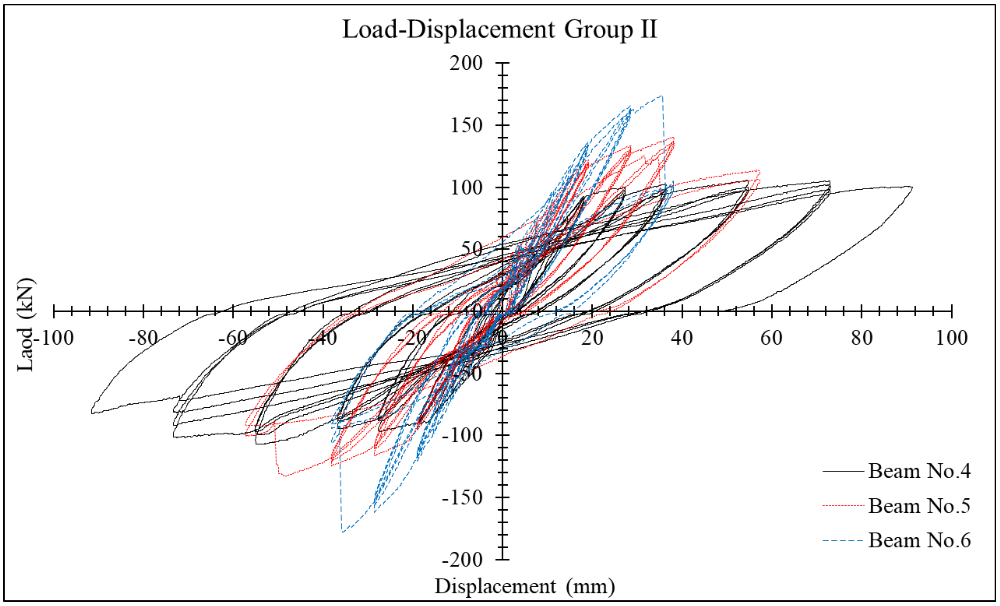

Fig. 6: Load-Displacement response of group II

4. Comparison of Specimen Responses

The seismic performance will be compared for all specimens in the following sections.

4.1. Energy Dissipation

The energy dissipation values, converted to kN-mm, reveal the impact of CFRP thickness, steel size, and concrete compressive strength on the cyclic performance of the beams. Beams with No. 13 steel and low concrete compressive strength generally dissipated more energy than those with No. 16 steel and high concrete strength, indicating higher ductility in the former group. Beam 1 (control) exhibited the highest energy dissipation, at 56,495 kN-mm, due to its ductile behavior and absence of CFRP constraints. Beam 2 (thin CFRP) dissipated 12,429 kN-mm, significantly less than the control, as the CFRP restricted cracking and deformation. Beam 3 (thick CFRP) dissipated the least energy in this group, at 8,474 kN-mm, reflecting the reduced ductility and early debonding of the thick CFRP. In contrast, the beams with No. 16 steel and high concrete compressive strength dissipated less energy overall. Beam 4 (control) showed the lowest dissipation, at 6,437 kN-mm, due to the stiffer response of stronger steel and concrete. Beam 5 (thin CFRP) achieved better energy dissipation at 15,251 kN-mm, benefitting from enhanced strength and restrained cracking provided by thin CFRP. Beam 6 (thick CFRP) dissipated 9,040 kN-mm, showing a slight improvement over Beam 4 but still limited by reduced ductility and CFRP debonding. Overall, thin CFRP sheets offered a better balance of strength and energy dissipation compared to thick CFRP sheets, while beams with No. 13 steel and lower concrete strength exhibited greater energy absorption during cyclic loading, highlighting their ductile behavior. The comparison of energy dissipation as well as peak load and displacement are shown in Figure 7.

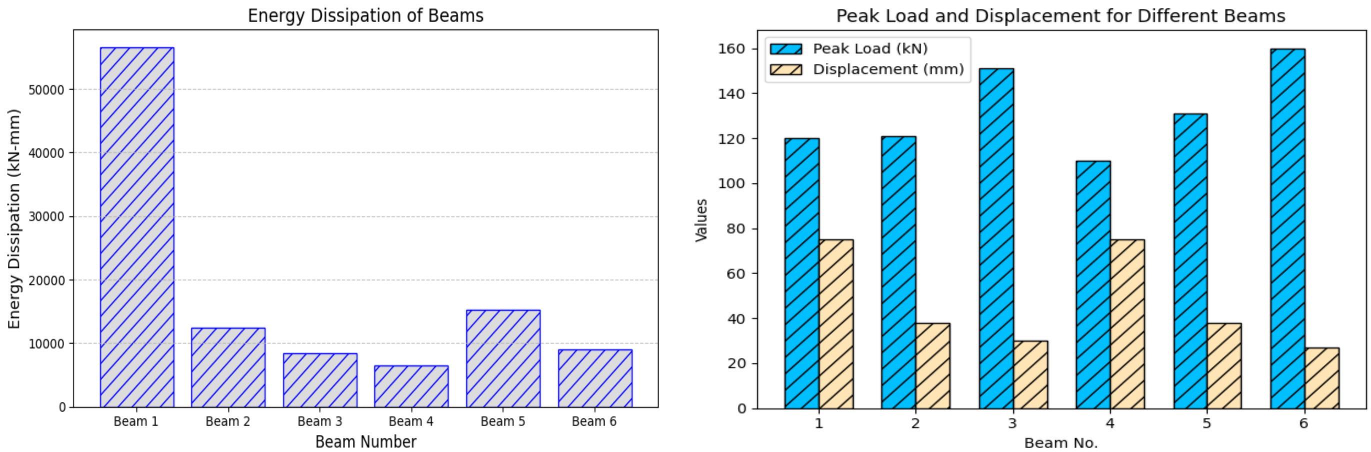

Fig. 7: Energy dissipations, peak load and displacement comparison

4.1. Strength and Ductility

The performance of the six beams highlights the combined effects of CFRP thickness, steel size, and concrete compressive strength on cyclic behavior. Beams with thin CFRP sheets demonstrated a good balance of strength and ductility. For instance, beam 2 (low-strength concrete) sustained significant displacements of 47.75 mm before failure, while Beam 5 (high-strength concrete) showed increased strength but reduced ductility due to the stiffness provided by stronger concrete. In contrast, beams with thick CFRP sheets achieved higher strength but reduced ductility, as seen in Beam 3 (30.00 mm displacement) and Beam 6, where debonding was a dominant failure mode despite superior strength.

The steel size significantly influenced the beams' responses. Beams with No. 13 steel exhibited greater ductility, particularly in the control beam, while those with No. 16 steel demonstrated higher stiffness and strength but less energy dissipation. High concrete compressive strength also improved stiffness, crack control, and ultimate loads, especially in thick CFRP configurations, though it reduced ductility compared to beams with low-strength concrete. Overall, thin CFRP sheets balanced ductility and strength, while thick CFRP sheets maximized strength at the expense of energy dissipation and ductility, particularly in beams with larger reinforcement and stronger concrete.

4. Conclusion

This study highlights the influence of CFRP thickness, concrete strength, and steel reinforcement detailing on the cyclic performance of RC beams. The results demonstrate that beams strengthened with thin CFRP sheets achieve a better balance between strength and ductility, offering significant energy dissipation while maintaining sufficient flexibility. In contrast, beams with thick CFRP sheets exhibited higher strength but reduced ductility, primarily due to early debonding failures. Beams with lower-strength concrete and smaller reinforcement showed enhanced ductile behavior and greater energy absorption under cyclic loading compared to those with higher-strength concrete and larger reinforcement. The findings emphasize the potential for tailoring CFRP configurations to specific performance goals, such as enhancing energy dissipation or maximizing strength. Future research should explore advanced anchoring techniques and hybrid strengthening methods to further optimize the cyclic performance of CFRP-strengthened RC members.

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