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Strengthening of Reinforced Concrete Cantilever Beams by Using Externally Bonding and Near-Surface Mounting Strengthening Techniques

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Keywords:

Carbon fiber reinforced polymers (sheet and laminate); Experimental work; Flexural behavior; Reinforced concrete cantilever beams; Strengthening techniques.

Highlights:

- *Behavior and strength of cantilever subjected to point load.*
- *Reinforced with CFRP strip, CFRP laminate as an External bounding and Near Surface Mounted technique.*

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Abstract: This research aims to study the efficiency of using different strengthening techniques to strengthen the reinforced concrete cantilever beams. Carbon fiber reinforced polymer (CFRP) strips and laminates with different patterns are used for this purpose. The practical program consisted of casting and testing of nine reinforced concrete cantilever beams (RCC). All these specimens had the same dimensions of (200×300×1250) mm, as well as the same main and secondary reinforcement. One of these beams was considered a reference beam with no strengthening, while the other eight beams were strengthened with the mentioned strengthening techniques. The strengthening variables included the type of CFRP (strips or laminate), the number (or equivalent area) of strips and the laminates, and the strengthening technique (external bonded EB and near surface mounted NSM). All specimens were tested until failure under point load at the free end of the beams. The results showed that all the used strengthening techniques increased the strength of beams for ultimate load and stiffness, with increasing ratios ranging from 37% to 67%. The strengthened tested beams noticeably increased with the CFRP layer (or area) for both types of CFRP (strips and laminates). Also, the CFRP laminate showed a higher effect in the increase in beam strength than the CFRP strips. Related to the strengthening technique, the Near Surface Mounted technique showed a higher effect in increasing beam strength than the External Bonded technique for different strengthening types and amounts.

تقوية العتبات الناتئة الخرسانية المسلحة باستخدام تقنيات الترابط الخارجي والتثبيت القريب من السطح

عبدالرحمن سطام احمد، مازن برهان الدين عبدالرحمن
قسم الهندسة المدنية/ كلية الهندسة/ جامعة تكريت / تكريت - العراق.

الخلاصة

يهدف هذا البحث إلى دراسة كفاءة استخدام تقنيات التقوية المختلفة لتقوية العتبات الناتئة الخرسانية المسلحة. تم استخدام شرائط وصفائح البوليمر المقوى بألياف الكربون (*CFRP-strips*) و(*CFRP-laminate*) بأنماط مختلفة. يشمل البرنامج العملي صب واختبار تسع عتبات ناتئة من الخرسانة المسلحة (*RCC*). جميع هذه العتبات لها نفس الأبعاد (٢٠٠ × ٣٠٠ × ١٢٥٠) ملم وكذلك نفس التسليح الرئيسي والثانوي. تعتبر إحدى هذه العتبات عتبة مرجعية بدون تقوية، بينما تم تقوية العتبات الثمانية الأخرى بتقنيات التقوية المختلفة. متغيرات التقوية تضمنت نوع ال *CFRP* (شرائط أو صفائح)، وعدد (أو مساحة مكافئة) الشرائط والصفائح، وتقنيات التقوية (*EB* الترابط الخارجي و*NSM* تقنية التركيب القريب من السطح). تم اختبار جميع العتبات الناتئة باستخدام حمل مركز في نهاية العتبة حتى الفشل. أظهرت النتائج أن جميع تقنيات التقوية المستخدمة أدت إلى زيادة قوة التحمل القصوى والصلابة بنسب زيادة تراوحت بين (٣٧٪) إلى (٦٧٪). جميع العتبات المختبرة المقوية لها زيادة ملحوظة مع زيادة طبقة (أو مساحة) الـ *CFRP* لكلا النوعين (الشرائح والصفائح). كما أن صفائح ال (*CFRP*) أظهرت تأثيراً أعلى في زيادة قوة العتبات مقارنة بشرائط ال (*CFRP*). فيما يتعلق بتقنيات التقوية، أظهرت تقنية التركيب القريب من السطح (*NSM*) زيادة أعلى في قوة العتبة الناتئة مقارنة بتقنية الترابط الخارجي (*EB*) وبحسب انوع التقوية المختلفة.

الكلمات الدالة: العتبات الناتئة ، شرائط وصفائح ال(CFRP) ، تقنيات التقوية (تقوية مقيدة خارجيا وتقنية التركيب القريب من السطح) ، دراسة سلوك الانحناء.

1.INTRODUCTION

A reinforced concrete cantilever beam is a structural element that extends horizontally, and it is supported at only one end. It is frequently used in construction to provide support for balconies, roofs, and overhangs. Additionally, it is utilized in bridges and other construction to extend decks over obstructions. When a cantilever beam is subjected to loads, the upper fibers experience tension, while the lower fibers experience compression stresses. Cantilever beams can be constructed from different materials, such as concrete, steel, wood, or composite materials. Selecting a material for constructing cantilever beams depends on the specific requirements of the project, including load-bearing capacity, durability, and aesthetic considerations [1]. In recent years, many techniques have been invented for the repair and strengthening of reinforced concrete elements. Among these methods, the use of carbon fiber reinforced polymer (CFRP) has proven to be one of the most efficient techniques. CFRP material can be a perfect alternative to traditional building materials for rehabilitating, reinforcing, and repairing existing reinforced concrete RC structures. It can also be used as an alternative to steel reinforcement in new constructions [2]. Use fiber-reinforced polymer (FRP) to improve the performance of concrete structures, with a specific emphasis on cantilever beams. Various methods of FRP strengthening, such as near-surface mounted and external bonding, are used. The studies show cases of strengthening cantilever beams in balconies in Daqing, China. The process of strengthening was as follows. Three carbon fiber sheets, each measuring 100mm wide, were pasted at an interval of 250mm on the outer end of each cantilever beam. Each beam had a 150 mm lapped at the top, and four corners of each beam had a 15 mm deep groove. The use of FRP strengthening is shown to improve the mechanical behavior and performance of strengthened concrete cantilever beams, prolonging the service life of structures and reducing engineering costs [3]. Their study aimed to investigate the influence of CFRP laminate as a strengthening material on the flexural behavior of hollow concrete cantilever beams. Experimental study and theoretical analysis were conducted to compare the performance of beams with and without CFRP laminate. The results consistently demonstrated that the addition of CFRP laminate significantly enhanced the cantilever beams' ultimate strength and stiffness, while having minimal effect on ductility. Using ANSYS theoretical modeling closely matched the experimental findings, highlighting the effectiveness of CFRP laminate in enhancing the strength and ductility of cantilever beams [4]. Investigating the interfacial stresses in reinforced concrete (RC) cantilever beams that have been reinforced with different materials, such as composite plates and FRP laminate plates. The study examined the effect of parameters, such as plate stiffness, adhesive layer thickness, and fiber orientation, on interfacial stresses. The research provided insights for engineers to optimize design parameters for reinforced RC cantilever beams and prevent debonding, with a focus on bending and shear deformations and concentrations of stress [5]. The enhancement of the flexural strength of reinforced concrete beams was examined by utilizing carbon fiber reinforced polymer (CFRP) strips with grooves. The results showed improvement in the load-carrying capacity of the strengthened beams compared to the control beams. The rectangular grooves showed the most significant improvement. Concrete cover separation has been observed in all grooved beams, suggesting effective bonding between the CFRP and the concrete surface. In summary, the study showed that the CFRP successfully strengthened the flexural capacity of the strengthened concrete beam [6]. The strength of concrete corbels (short cantilever) was improved by utilizing CFRP strips and external CFRP plates. The investigation studied strengthening different CFRP configurations to enhance the cracking and ultimate loading. Specifically, external CFRP plates significantly increased ultimate loads, and the diagonal wrapping configuration was more effective than horizontal full wrapping. Strengthening with CFRP plates resulted in higher load-bearing capacity and deflection before failure than the CFRP fabric sheets. Horizontal CFRP strips increased the ultimate load capacity up to 84.21%, while inclined CFRP strips showed an increase of up to 92.1% [7]. The authors focused their research on investigating the response of reinforced concrete tapered beams strengthened using NSM-CFRP laminates. The experimental program included testing of nine specimens, with one group of unstrengthened reference beams and another group of beams strengthened with NSM-CFRP strips. The results indicated that as the angle of inclination increased, the ultimate load capacity decreased for unstrengthened beams; however, it increased for strengthened beams. The NSM-CFRP technique demonstrated potential in enhancing the shear resistance of RC beams. Overall, the study found that strengthening tapered concrete beams with NSM-CFRP strips increased the ultimate load capacity of the beams, with the UL-strips pattern showing the highest increase. The deflection at ultimate load was also reduced with strengthening [8]. The study investigated the impact of jute fibers on the behavior of ferrocement slabs. Three primary instances of slab reinforcement under impact loads were examined. In the first case, a square sheet of jute fibers with dimensions of 250×250 mm was subjected to the impact load at the center of the slab. In the second case, jute fibers were positioned in two perpendicular orientations, with a distance of 50×450 mm, leaving a clear gap of 50 mm between them. While in the third case, the jute fibers were positioned in two orientations, with a distance of 100×450 mm, leaving a clear gap of 75 mm between them. The results showed that strengthening slabs with jute fiber strips significantly improved the impact load strength. The best results were achieved when 50 mm-wide strips were used, enhancing failure statuses by 722.58%, 232.26%, and 206.18% compared to reference specimens [9]. The wire mesh-epoxy composites were investigated to improve the performance of concrete beams. The results showed that wire mesh with epoxy significantly enhanced flexural strength, cracking behavior, and energy absorption capability. The wire mesh-epoxy composite was more efficient in flexural strength and ductility than carbon fiber. A hybrid wire mesh-epoxy-carbon fiber composite had significantly higher energy absorption capability than specimens bonded with only carbon fiber [10]. The effect of impact loads on reinforced concrete beams strengthened with carbon fibers and steel wire rope was investigated. The study compared results from reference beams, steel wire rope beams, and carbon fiber beams. The results showed a decrease in maximum deflection, residual deflection, damping time, and strike number. The best results were achieved when strengthening with a steel rope with or without carbon fibers, improving dynamic deflection, residual deflection, damping time, and strike number [11]. The effect of static loads on concrete beams strengthened with wire rope. Using steel wire rope was suggested as a new economical technique for strengthening reinforced concrete beams. The study found that using wire rope with CFRP increased flexural strength, hardness, and toughness, while decreasing maximum deflection. Additionally, wire ropes with CFRP increased splitting strength and prevented concrete cover separation. The wire rope's potential was highlighted for resisting flexure, shear, and torsion stresses due to ease of forming into the required shape. Moreover, increasing the rope's diameter or reducing the spacing between the wrapped rope's segments enhanced its efficiency, rendering strengthening by wire rope a new, efficient, and economic technology [12]. The present study aims to investigate the global behavior and strength of reinforced concrete cantilever beams using CFRP strips and laminates. The study included different configurations using the External Bounding and Near Surface Mounting.

2.MATERIALS

2.1.Materials and Specimen Proportions

- **Cement:** The cement used in casting all specimens was Ordinary Portland cement (Type I) that complies with the criteria of IQS No.5/1984 [13].
- **Fine Aggregate:** Natural Iraqi sand river was used in experimental work, which complies with the specifications stated in IQS NO.45/1984 [14].
- **Coarse Aggregate:** Natural Iraqi river gravel was used in experimental work. The maximum Agg size of 12.5 mm with the specifications outlined in IQS No.45/1984 [14].
- **Water:** The water tap was used for curing and mixing of all specimens.
- **Steel bars:** Deformed steel bars with a diameter of 16 mm (for flexural

reinforcement), 12 mm (for compression zone), 10 mm and 6 mm (for columns and shear reinforcement) were used. Table 1 presents the properties of the steel bars used. These bars conform to the specifications outlined in ASTM A 615 [15].

2.1.1.Concrete Mix Design

Table 2 displays the weight-based mixture proportions utilized in the experimental work, as per the ACI 211.1-91 standard [16].

Table 1 Properties of Steel Reinforcement Bars.

Bar Diameter (mm)	Actual Diameter (mm)	Yield Stress fy (MPa)	Ultimate Stress fu (MPa)	Elongation %
6	5.67	432.9	569.80	6.33
10	9.89	530	625.89	9.38
12	12	575	662	12.6
16	15.96	614.67	707.04	11.19

Table 2 Mix Proportion.

Materials	W/C	Water	Cement	Fine. A	Coarse. A
Quantity (kg/m³)	0.457	160	350	850	1040

2.1.2.Strengthening Material

A. Carbon Fiber Reinforced Polymers CFRP strips, named Sika (Wrap®-300 C), woven black unidirectional Carbon Fiber Reinforced Polymers CFRP fabric, were used for the structural EB and NSM strengthening of the cantilever in the present work.

B. CFRP laminate, commercially named (Sika CarboDur ®-1012 E), unidirectional pultruded corrosion-resistant Carbon Fiber Reinforced Polymers CFRP laminate, was used for the structural EB and NSM strengthening of the cantilever beam.

Table 3 Mechanical Properties of the Used CFRP Material.

Type CFRP	Tensile Strength MPa	Modulus of Elasticity GPa	Thickness mm	Fiber Density g/cm³	Elongation at Break %
Sika Wrap-300 C	4000	230	0.167	1.82	>1.7
Sika CarboDur 1012E	2000	170	1.2	1.60	>1.18

2.1.3.Adhesive Substance

A. Epoxy (Sikadur®-330) consisted of two elements: component A (white) and component B (light gray). The CFRP standard recommends using strips of CFRP with a layer thickness of 0.167 mm for adhering to the surface of concrete.

B. Epoxy (Sikadur®-30LP) consisted of two elements: component A* (white) and component B* (black). The CFRP standard recommends attaching a carbon fiber reinforced polymer (CFRP) laminate, 1.2 mm thick, to the surface of concrete.

2.2.Cantilever Specimen Detail

The dimensions of each cantilever specimen were (300×200×1250) mm, fixed to a column of dimensions (200×300×700) mm, and a continuous beam with dimensions (200×300×800) mm, as shown in Fig. 1.

2.2.1.Details of Steel Reinforcement

The main (tension) reinforcement for the cantilever and column used deformed steel bars of a specific diameter of 16 mm. The tie bars used deformed steel bars with a diameter of 6 mm, and 10 mm was used for the columns, in addition to the reinforcement used to resist shear forces in the cantilever, as shown in Fig. 1.

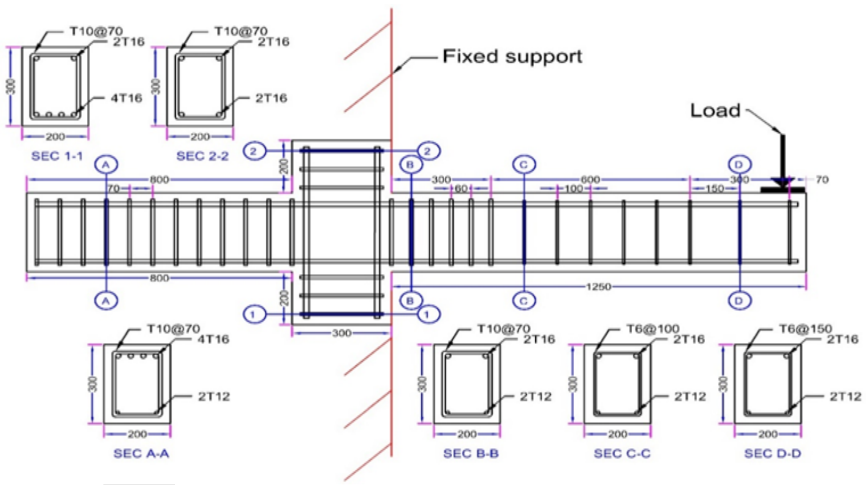


Fig. 1 Details and Reinforcement of Cantilever Specimen.

2.3. Experimental Program

The experimental program included pouring and testing up to failure of nine cantilever beam specimens of dimensions (200×300×1250) mm, fixed to a column of dimensions (200×200×700) mm, and a continuous beam of dimensions (200×300×800) mm, to examine the behavior and strengthening of the cantilever. The specimens were divided into two groups in addition to the reference (unstrengthened) specimen: The first group represents four RCC beams that were strengthened with CFRP strips, one and two layers. The second group represents four RCC beams that were strengthened with CFRP laminate (CarboDur) using one and two plates (5 cm and 10 cm), as shown in Table 4. The dimensions of the cantilever and column, as well as the main and secondary reinforcement, remained constant for all specimens.

*The CFRP strips material has been rewarded based on the use of CFRP-Laminate material, as it was). Tensile strength for CarboDur 2000MPa divided by area (1.2mm-thickness and 50mm-wide; the load was 120kN. For CFRP-strips, tensile strength for CarboDur 4000MPa divided by area (0.167 mm-thickness and 180 mm-wide); the load was 120kN. All specimens were rewarded in the same way as described previously [17].

Table 4 Variables of the Tested Cantilever Beams.

Beam Group	Beam Designation	CFRP Type	Number of CFRP (strips or laminate)	Technique EB or NSM	Width of CFRP strip/laminate mm
Reference	A1	control cantilever (un-strengthened)			
CFRP Strips	B1	CFRP-strips	One	EB	180
	B2	CFRP-strips	Two	NSM	180
	B3	CFRP-strips	One	EB	180
	B4	CFRP-strips	Two	NSM	180
CFRP Laminates	C1	CFRP-laminate	One	EB	50
	C2	CFRP-laminate	Two	NSM	100
	C3	CFRP-laminate	One	EB	50
	C4	CFRP-laminate	Two	NSM	100

2.4. Strengthening Details

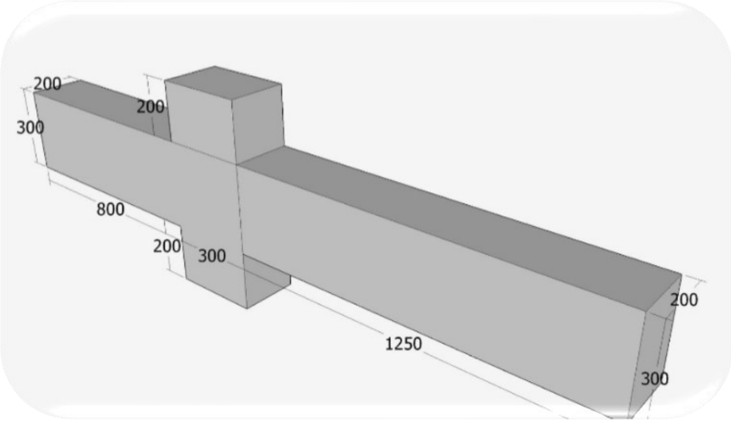
The specific elements that contribute to the strengthening are as follows:

2.4.1. The CFRP Strips

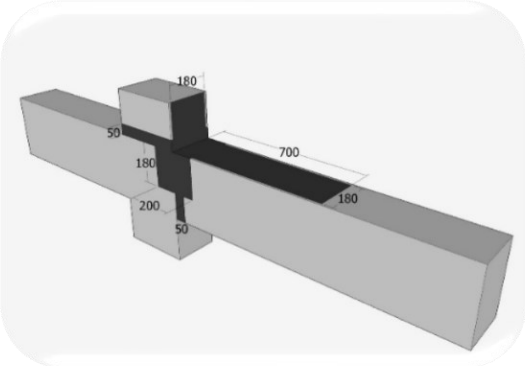
- **External bonding (EB):** The concrete cantilever beam specimens (B1) and (B2) were provided with one layer and two layers of CFRP strips, respectively. A size of 700 mm in length attached to the upper surface of the cantilever beam, and 180 mm wide, was placed in an L shape. This layer was extended to the side face of the column with a length of 200 mm. To prevent the CFRP from debonding, it was fixed by wrapping two sheets of CFRP for a width of 50 mm, around the perimeter of the column and the cantilever beam, as shown in Fig. 2, using an adhesive with epoxy(Sikadur®-330).
- **Near-Surface Mounted (NSM):** The concrete cantilever beam specimens (B3) and (B4) were provided with one layer and two layers of CFRP strips, respectively. A size of 700 mm in length was attached in a groove to the upper surface of the cantilever beam, and a 180 mm wide layer was placed in an L shape. This layer was extended to the side face of the column with a length of 200 mm. To prevent the CFRP from debonding, it was fixed by wrapping two sheets of CFRP, 50 mm wide, around the perimeter of the column and the cantilever beam, as shown in Fig. 2, using an adhesive with epoxy(Sikadur®-330).

2.4.2. The CFRP Laminate (CarboDur)

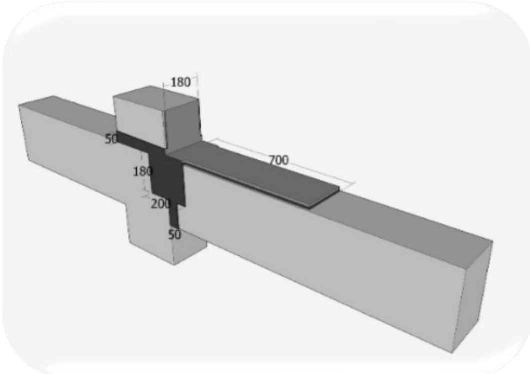
- **External bonding (EB):** The concrete cantilever beam specimens (C1) and (C2) were provided with one laminate(50mm) and two laminate(100mm) for the CarboDur, respectively, with size of 700 mm in length; it was placed in a hole inside the column of a depth of 100 mm and continues attached to the upper surface of the cantilever beam, i.e., 50 mm and 100 mm wide, respectively. To prevent the CFRP from debonding, it was fixed by wrapping two sheets of CFRP for a width of 50 mm, around the perimeter of the column and the cantilever beam, as shown in Fig. 2, using an adhesive with epoxy (Sikadur®-30LP).
- **Near-Surface Mounted (NSM):** The concrete cantilever beam specimens (C3) and (C4) were provided with one laminate (50mm) and two laminates (100mm) for the CarboDur, respectively, with a size of 700 mm in length, which was attached in a groove to the upper surface of the cantilever beam. 50 mm and 100 mm wide, respectively, were placed in an L shape. This layer was extended to the side face of the column with a length of 200 mm. To prevent the CFRP from debonding, it was fixed by wrapping two sheets of CFRP, each 50 mm wide, around the perimeter of the column and the cantilever beam, as shown in Fig. 2, using an adhesive with epoxy (Sikadur®-30LP).



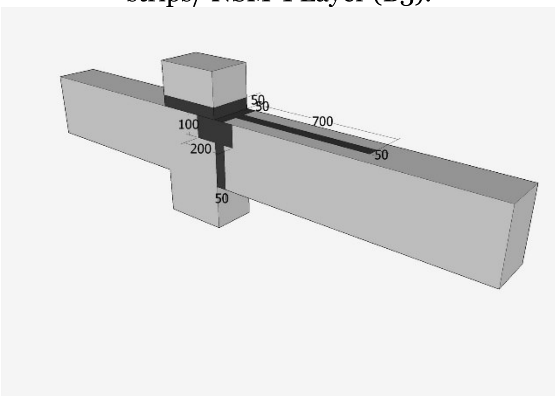
(a) Reference



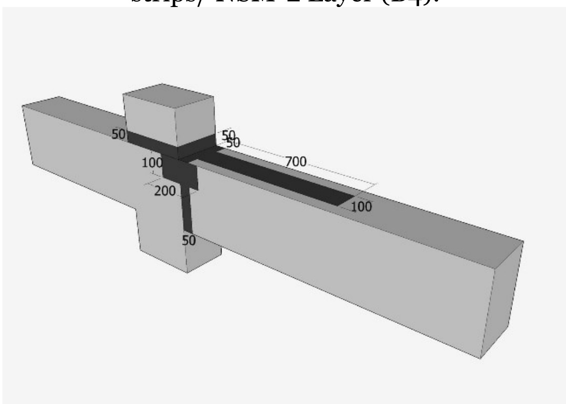
(b) CFRP-strips/ EB-1 Layer (B1) and CFRP-strips/ NSM-1 Layer (B3).



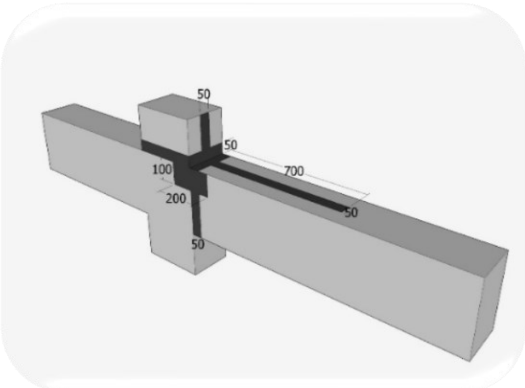
(c) CFRP-strips/ EB-2 Layer (B2) and CFRP-strips/ NSM-2 Layer (B4).



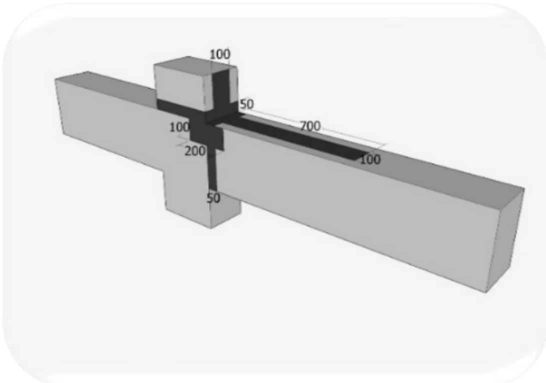
(d) CFRP-laminate/ EB-1plates (5cm) (C1).



(e) CFRP-laminate/ EB-2plates (10cm) (C2).



(f) CFRP-laminate/ NSM-1plates (5cm) (C3).



(g) CFRP-laminate/ NSM-2plates (10cm) (C4)

Fig. 2 Strengthening Details for Concrete Cantilever.

2.5.Testing Procedure

2.5.1.Loading of Specimen

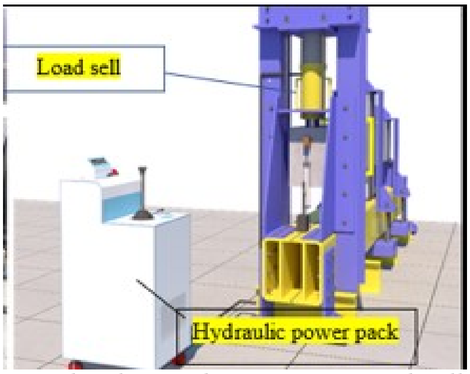
The cantilever beams were tested in the Structures laboratory, Tikrit University, using a Flexural testing machine of 300kN maximum capacity with a load rate of 0.5 kN/sec. The load was applied using a "Loading Cell" positioned on the end of the cantilever.

2.5.2.Deflection Measurement

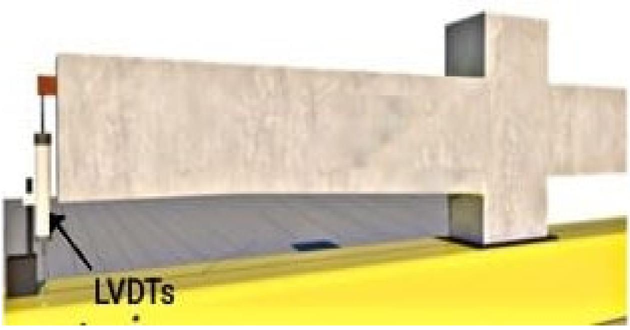
Vertical deflection was measured using linear variable differential transformers (LVDTs). The LVDTs were placed attached to the front face of the cantilevered beams.

2.5.3.Data Test

The test data; such as load, strain, and deflection; were collected using a data logger. Figs. 3 and 4 present the laboratory's testing procedures.

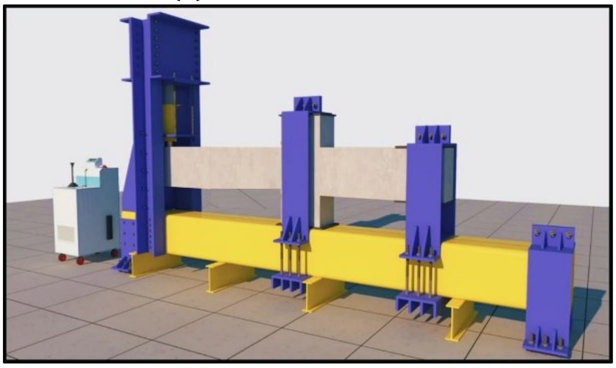


(a) Hydraulic Loading System (Load Sell).



(b) LVDTs Installation.

(c) Data Logger Device.



(d) Cantilever Specimens.

Fig. 3 Testing of Specimens.

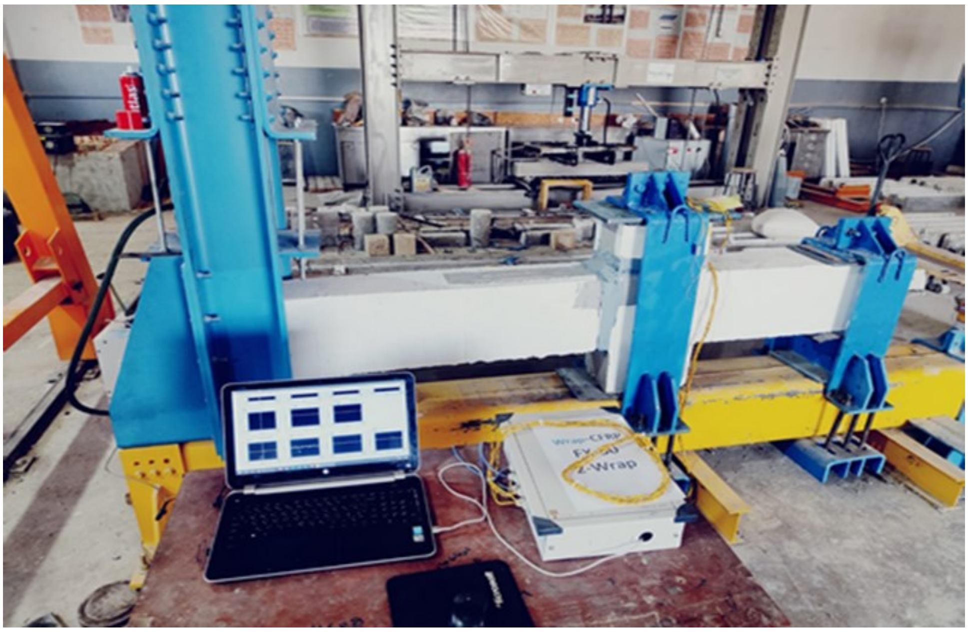


Fig. 4 Loading Technique and the Test Setup.

3.CONCRETE'S MECHANICAL PROPERTIES

The concrete compressive strength (f_{cu}) of concrete was determined according to specifications outlined in ASTM C39-14 [18], found to be (29.89 MPa). Also, the splitting tensile strength (f_t) was determined according to ASTM C496 M-04 [19], found to be (4.07 MPa).

4.RESULTS AND DISCUSSION

4.1.Load-Deflection Relationship

The load-deflection curves for all tested cantilever beams are shown in Figs. 5 and 6. When the ultimate load was applied to the end of the cantilever, it reached failure. The results showed that the deflections of strengthened cantilever beams showed a significant decrease compared to the reference cantilever beam under the same load conditions. The ultimate deflection at failure was 98.07mm for the control beam, where it decreased to 43.34 mm after strengthening, when using CFRP strips NSM(2-layer) technique. Table 6 shows the final results of all the cantilever beam experiments.

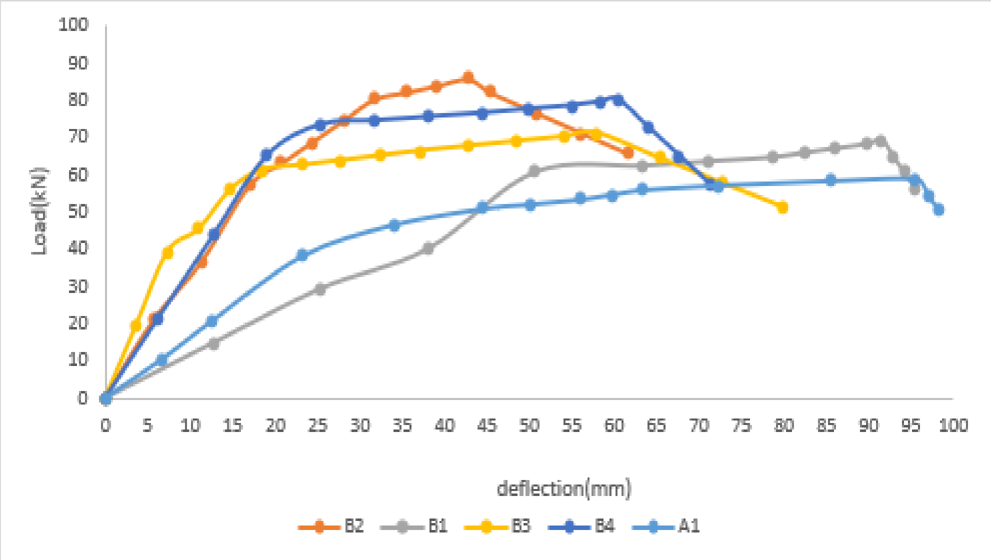


Fig. 5 Load–Deflection Curves for the 1st Group CFRP-Strips.

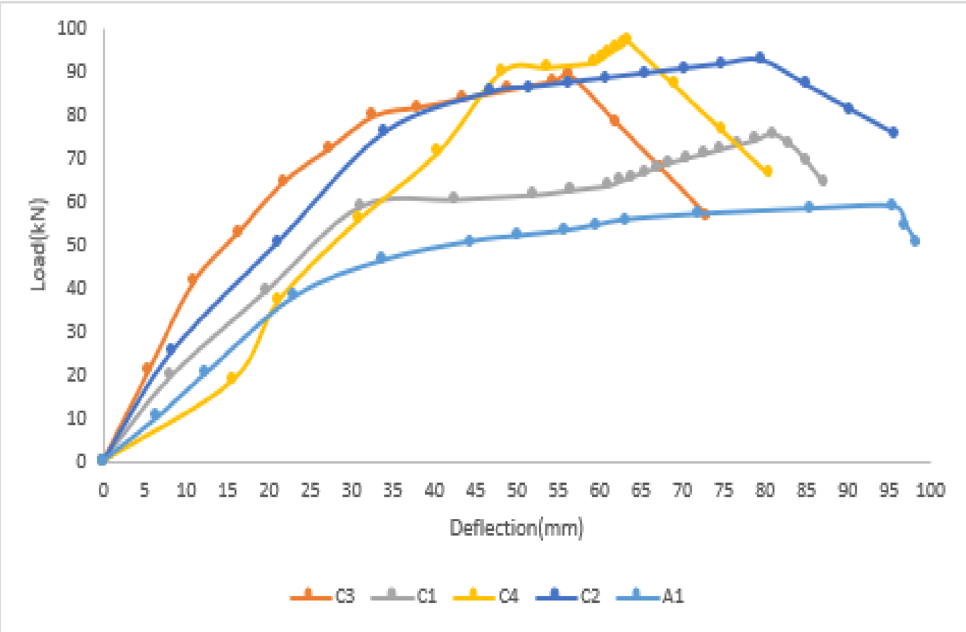


Fig. 6 Load–Deflection Curves for the 2nd Group CFRP-Laminate.

4.2.Load-Deflection Response of Cantilever Beams

Table 5 and Figs. 5 and 6 demonstrate the effects of strengthening on the deflection response of a cantilever beam.

- **For Group One** of specimens strengthened using CFRP-Strips, the maximum deflection (deflection at failure) of the cantilever beam strengthened using the EB technique with one and two layers (B1 and B2) increased by approximately 16% and 34%, respectively, compared to the reference specimen. While for specimens strengthened using the (NSM) technique with one and two layers (B3 and B4), the mentioned deflection increased by approximately (42% and 44%) compared with the reference specimen.

- **For Group two** of specimens strengthened using CFRP-laminate, the maximum deflection (deflection at failure) of the cantilever beam strengthened using the EB technique with one and two laminates (C1 and C2) increased by approximately 17% and 19%, respectively, compared to the reference specimen. While for specimens strengthened using the NSM technique with one and two laminates (C3 and C4), the mentioned deflection increased by approximately 42% and 35%, respectively, compared to the reference specimen.

4.3. Ultimate Load

The results indicated that the ultimate load capacity of the reference cantilever beam was 59.897 kN.

- **For Group One** of specimens strengthened using CFRP-Strips, the ultimate load (load at failure) of the cantilever beam strengthened using the EB technique with one and two layers (B1 and B2) increased by approximately 16% and 34%, respectively, compared to the reference specimen. While for specimens strengthened using the NSM technique with one and two layers (B3 and B4), the mentioned load increased by approximately 19% and 37%, respectively, compared to the reference specimen.
- **For Group two** of specimens strengthened using CFRP-laminate, the ultimate load (load at failure) of the cantilever beam strengthened using the EB technique with one and two laminates (C1 and C2) increased by approximately 26% and 55%, respectively, compared to the reference specimen. While for specimens strengthened using the NSM technique with one and two laminates (C3 and C4), the mentioned load increased by approximately 49% and 63%, respectively, compared to the reference specimen.

Table 5 Main Test Results.

Group No	Cantilever specimen	P_{cr} kN	P_{yield} kN	P_u KN	Increasing of P_u %	Δ_u (mm)	Toughness kN.mm	Failure Mode
G-0 Reference	A1	13	28	59.897	----	98.07	95.01	SY → CC
G-1 CFRP-Strips	B1	15	60	69.28	16	92.43	123.05	SY → RUP and DEB
	B2	20	58	80.167	34	60.69	189.08	SY → DEB
	B3	19	62	71.167	19	56.94	161.09	SY → RUP
	B4	20	67	82.179	37	43.34	155.51	SY →DEB
G-2 CFRP-Laminate	C1	18	60	75.706	26	81.19	480.18	SY →DEB
	C2	19	78	92.698	55	79.86	149.22	SY →PRUP
	C3	20	80	89.324	49	57.24	161.64	SY → PRUP
	C4	18	90	97.489	63	63.87	683.18	SY →PRUP

where P_{cr} is cracking load, P_y is yield load, Pu is ultimate load, Δ_u is ultimate deflection at the free end cantilever at ultimate load, SY is steel yielding, CC is concrete crushing, RUP is rupture, DEB is debonding, and PRUP is partial rupture.

4.4. Effect of Strengthening Techniques

The effects of strengthened techniques (Externally bounding CFRP strip and CFRP laminate (CarboDur), and near-surface-mounted CFRP strips and CFRP laminate (CarboDur)) on the maximum load capacity are shown in Fig. 7.

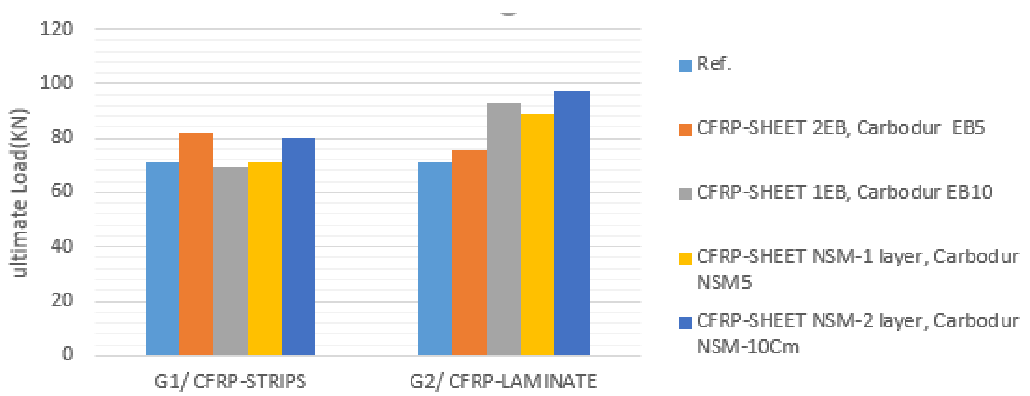


Fig. 7 Effects of Strengthened Techniques.

The following can be observed from Fig. 7:

- **When the strength type of external bounding**, it can be observed that an increase in the ultimate load of cantilever beam CFRP-strips (B1 and B3) by about 16% and 19%, respectively, compared to the reference. Also for CFRP-laminate (CarboDur) (C1 and C3), the ultimate load increased by about 26% and 49%, respectively, compared to the reference.
- **When the strength type of Near Surface mounting**, it can be observed an increase in the ultimate load of cantilever beam CFRP-strips (B2 and B4) by about (34% and 37%), respectively, compared to the reference, also for CFRP-laminate (CarboDur) (C2 and C4), the ultimate load increased by about (55% and 63%), respectively, compared to the reference.

Generally, the maximum loads of cantilevers reinforced with near-surface-mounted CFRP strips and CFRP laminate were higher than the maximum loads of cantilevers reinforced with externally bonded CFRP strips and CFRP laminate, or specimens that were not reinforced.

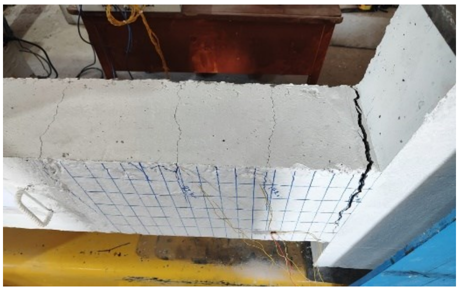
4.5.Failure Mode

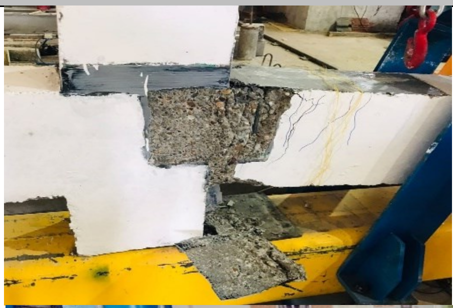
The reference cantilever beam displayed a flexural mode of failure, with first cracking on the tensile side with a vertical load of around 13 kN. Upon additional loading, cracks propagated on both sides of the cantilever beam until the internal main steel reached its yield point, widening and lengthening the primary cracks. Finally, the cantilever beam failed due to tension-controlled flexural failure mode, and then the concrete on the lower face of the cantilever beam was crushed, as illustrated in Fig. 8(a).

- **Group one:** For specimens strengthened with CFRP-strips material, the specimens displayed flexural cracks at higher loads compared to the reference specimens (unstrengthened).

Generally, for all cantilever beams strengthening, the first flexural cracking occurred at loading (15-20) kN, which showed slight changes compared to those of the reference cantilever. Upon additional loading, specimens showed flexural cracks and eventually failed due to a flexural mode of failure, as shown in Fig. 8 (c and e). For specimens (B2) and (B4), the failure occurred due to the steel bar yielding, which was then followed by debonding of the CFRP strips from the side strengthened, followed by crushing of the concrete. While for specimen (B1), the failure occurred due to rupture and debonding of CFRP strips instead of debonding. (Fig. 8(b)). Also, for specimen (B3), the failure occurred due to rupture of CFRP strips instead of debonding (Fig. 8(d)).

- **Group two:** For specimens strengthened with CFRP-Laminate material, the specimens displayed flexural cracks at higher loads compared to specimens strengthened with CFRP-Strips. Generally, for all cantilever beams strengthening, the first flexural cracking occurred at a loading of (18-20) kN, which showed slight changes compared to those of the reference cantilever. Upon additional loading, specimens showed flexural cracks and eventually failed due to flexural mode of failure, as shown in Fig. 8 (g, h, and I). For specimens (C2), (C3), and (C4), the failure occurred due to the steel bar yielding, which was followed by partial rupture of the CFRP laminate from the side strengthening, then crushing of the concrete. While for specimen (C1), the failure occurred due to debonding of the CFRP-Laminate instead of partial rupture (Fig. 8(f)).

Group NO	Cantilever designation	SIDE VIEW	TOP VIEW
	Reference **(a)**		

Group NO	Cantilever designation	SIDE VIEW	TOP VIEW
	B1(b)		
G1. CFRP sheet	B2(c)		
	B3(d)		
	B4(e)		
	C1(f)		
G2. CFRP laminate	C2(g)		

Group NO	Cantilever designation	SIDE VIEW	TOP VIEW
	C3(h)		
	C4(I)		

Fig. 8 Failure Modes for the Tested Cantilever Beam

5.FLEXURAL TOUGHNESS

Toughness, as per ASTM C1018 [20] and ACI 544.4R-88Report, 1988[21], refers to the total energy that a specimen can absorb before it fails. Toughness can be determined by calculating the area under the load-deflection curve in flexure. The results are presented in Table 5. The minimal residual toughness was 30% for specimen (B1-EB) compared to the reference due to the debonding and rupture of the CFRP strips. The highest toughness reached 600% for spacemen (C4-NSM 2 plates) compared to the reference cantilever.

6.CONCLUSIONS

Different strengthened techniques have been adopted and applied to increase the strength of the cantilever beam. According to the present study, the following conclusions can be drawn:

1- All strengthened cantilever beams showed improvement in ultimate load capacity and deflection. The failure load increase ranged between 16 to 63% compared to the reference cantilever beam at the same loading rate.

2- All strengthened cantilever beams showed a reduction in deflection ranging between 16 to 44% compared to the reference cantilever beam at the same loading rate.

3- Near-Surface strengthening (NSM) technique showed more efficient technique than externally bonding (EB) in increasing the strength of all tested specimens for several reasons, i.e., stronger and more durable bond due to the embedding of the CFRP within the concrete, better load transfer and structural performance, leading to more efficient strengthening, and greater protection from environmental factors, reducing maintenance needs.

4- Using CFRP-Laminate for strengthening showed a more efficient strengthening material than CFRP-Strip for all related specimens.

5- Using two strengthening layers instead of one strengthening layer led to an increase in the ultimate strength of all related specimens, i.e., an increase in the ratio range from (34%) to (37%).

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