Tikrit Journal of Engineering Sciences (2024); 31(1): 88-100
DOI: http://doi.org/10.25130/tjes.31.1.8

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Behavior of Reinforced Concrete Corbels Strengthened with CFRP Strips Subjected to Monotonic and Repeated Loading

Enas S. Ibrahim [a*], **Mazin B. Abdulrahman** [a], **Yasser I. Yahia** [b], **Belal Alsubari** [c], **Hayder S. Abdulaali** [d], **Shagea Alqawzai** [e]

a Civil Engineering Department, Engineering College, Tikrit University, Tikrit, Iraq.
b Architectural and Interior Design Department, Engineering College, Gulf University, Sanad 26489, Bahrain.
c Civil Engineering Department, Engineering College, Miami College of Henan University, Kaifeng, Henan, China.
d Architecture Engineering Department, Engineering and Built Environment College, Kebangsaan Malaysia University, Bangi, Selangor, Malaysia.
e Civil Engineering Department, Chongqing University, Chongqing 400045, China.

Keywords:
Corbels; CFRP Strips; Externally Bounded Strengthening; Repeated Loads.

Highlights:
- Behavior and strength of corbels subjected to monotonic and repeated loads.
- Strengthening with CFRP strips as an externally bounded technique.

ARTICLE INFO
Article history:

Received	20 Mar.	2023
Received in revised form	21 June	2023
Accepted	01 July	2023
Final Proofreading	22 July	2023
Available online	16 Feb.	2024

Citation: Ibrahim ES, Abdulrahman MB, Yahia YI, Alsubari B, Abdulaali HS, Alqawzai S. **Behavior of Reinforced Concrete Corbels Strengthened with CFRP Strips Subjected to Monotonic and Repeated Loading**. *Tikrit Journal of Engineering Sciences* 2024; **31**(1): 88-100.
http://doi.org/10.25130/tjes.31.1.8

*Corresponding author:
Enas S. Ibrahim
Civil Engineering Department, Engineering College, Tikrit University, Tikrit, Iraq.

Abstract: Concrete corbels are short cantilevers subjected to monotonic and repeated loads. Repeated loads generally negatively affect the concrete structural members' strength as they decrease the resistance to external loads. To increase these loads, strengthening with carbon fiber reinforced polymer (CFRP) strips as an externally bounded technique is used. This paper studies the behavior and strength of strengthened corbels subjected to monotonic and repeated (constant and incremental) loads. The experimental program included the casting and testing of twelve double-concrete corbels. All specimens have been kept constant for corbel dimensions and main and secondary reinforcement. Nine were strengthened with CFRP strips using different patterns, while the others were left un-strengthened as control corbels. The results showed that both repeated loads' types, i.e., constant and incremental, affected the ultimate load capacity of corbels. Compared to monotonic loading, a reduction occurred in ultimate load and ultimate deflection for corbels subjected to five repeated loading cycles. For corbels strengthened by externally bounded CFRP strips under any applied loads, the ultimate load significantly increased, while the ultimate deflection decreased compared to un-strengthened at the same applied load. All corbels failed by de-bonding the CFRP strips.

سلوك الكتائف الخرسانية المسلحة المقواة بشرائط CFRP المعرضة للتحميل الرتيب والمتكرر

ايناس صالح ابراهيم [١]، مازن برهان الدين عبدالرحمن[١]، ياسر ابراهيم يحيى [٢]، بلال الصباري [٣]، حيدر سعدون عبد العلي [٤]، شاجي الكوازي [٥]

[١] قسم الهندسة المدنية / كلية الهندسة / جامعة تكريت / تكريت - العراق.

[٢] قسم التصميم المعماري والداخلي / كلية الهندسة / جامعة الخليج / سند ٢٦٤٨٩، البحرين.

[٣] قسم الهندسة المدنية / كلية الهندسة / كلية ميامي في جامعة هنان / كايفينغ، هنان، الصين.

[٤] قسم الهندسة المعمارية / كلية الهندسة والبيئة المبنية / جامعة كيبانكسان ماليزيا / بانغي، سيلانكور، ماليزيا.

[٥] قسم الهندسة المدنية / جامعة تشونغتشينغ / تشونغتشينغ ٤٠٠٠٤٥، الصين.

الخلاصة

يتم تعريف الكتائف الخرسانية على أنها نتوءات قصيرة تتعرض لأحمال رتيبة ومتكررة. عادةً ما يكون للأحمال المتكررة تأثير سلبي على قوة العناصر الهيكلية الخرسانية لأنها تقلل من مقاومة الأحمال الخارجية. ولزيادة ذلك، يتم استخدام التقوية باستخدام شرائط البوليمر المقوى بألياف الكربون (CFRP) كتقنية المقيد خارجياً. في هذا البحث تم دراسة سلوك وقوة الكتائف المقواة التي تتعرض لأحمال رتيبة ومتكررة (ثابتة ومتزايدة). يشتمل البرنامج التجريبي على صب واختبار اثني عشر كتفاً خرسانياً مزدوجاً، وقد تم الحفاظ على جميع العينات ثابتة بالنسبة لأبعاد الكتائف، بالإضافة إلى التسليح الرئيسي والثانوي. تم تقوية تسعة منها بشرائط CFRP باستخدام أنماط مختلفة، بينما تُترك الأخريات دون تقوية ككتائف تحكم. أظهرت النتائج أن كلا نوعيّ الأحمال المتكررة (الثابتة والمتزايدة) قد أثرت على سعة الحمولة النهائية للكتائف، حيث حدث انخفاض في الحمل النهائي والانحراف النهائي للكتائف المعرضة لخمس دورات من التحميل المتكرر مقارنة بتلك التي تعرضت للتحميل الرتيب. بالنسبة للكتائف المقواة بشرائط CFRP المقيدة خارجيًا تحت أي نوع من الأحمال المطبقة، زاد الحمل النهائي بشكل كبير بينما انخفض الانحراف النهائي مقارنة بتلك غير المقواة عند نفس الحمل المطبق. فشلت جميع الكتائف عن طريق فك الترابط لشرائط CFRP.

الكلمات الدالة: كتائف، شرائط CFRP، تقوية مقيدة خارجياً، أحمال متكررة.

1.INTRODUCTION

In the ACI 318M [1] code, concrete corbels (or brackets) are defined as short cantilevers with a shear span to an effective depth (a/d) ratio less than unity. Because of this small ratio, the corbel's strength is mainly governed by shear, which tends to operate as deep beams or simple trusses rather than flexural members designed for shear. According to a study by Kriz and Raths [2], reinforced concrete corbels' most frequent failure modes can be summarized as flexural tension, flexure compression, diagonal splitting, sliding shear, bearing, and horizontal tension failure. In previous years, Fiber Reinforced Polymer (FRP) composite materials as externally bonded reinforcement for structural strengthening and rehabilitation of damaged or deteriorating members increased worldwide [3]. FRP is a composite material of discourteous fibers embedded in a polymeric matrix that makes several products, such as bars, structural sections, plates, and sheets [4]. This strengthening method has several advantages over conventional methods, such as low specific weight, low thermal expansion coefficient, and ease of handling and application [5]. FRP also has excellent fatigue properties; it is generally non-magnetic, corrosion-resistance, and chemically resistant. FRP has higher tensile strength and modulus of elasticity than concrete [6]. Also, this technique has disadvantages, such as FRP is a brittle material that cannot be applied to wet surfaces and has poor behavior at high temperatures [7, 8]. Furthermore, the costs are relatively high. CFRP strengthening material is almost the best because carbon fibers outperform glass and aramid fibers in Young's modulus, long-term behavior, fatigue behavior, and alkaline resistance [5]. Recent studies on reinforced concrete corbels are limited to the case of increasing loads monotonically; they do not answer any questions on the corbel's behavior under repeated loads. In practice, a structure can be subjected to repeated proportional or non-proportional high-intensity loading in several cases. Specimens with a high live load to dead load ratio, earthquake loading, and hurricane effects are examples of these. These types of loading cause higher strain and shear distress at critical sections. In seismic regions, using pre-cast concrete includes the development of a suitable connector between the pre-cast members [9-11]. Such connections between members must exhibit strength, ductility, and energy dissipation. Mohamad-Ali and Attiya [12] cast and tested thirty reinforced concrete corbels divided into four groups. Two groups were strengthened with horizontal externally bonded CFRP strips, and the other was strengthened with inclined externally bonded CFRP strips, using one, two, three, or four layers of CFRP strips. The results showed that compared to the control corbel ultimate load, specimens strengthened by inclined strips showed a (44.5 to 60) % increase, while specimens strengthened by horizontal strips showed a (14.7 to 31.2) % increase. CFRP strips also delayed the first cracks' appearance, with an increase in cracking load of (51.43) % for inclined techniques and (18.75) % for horizontal techniques. Shadhan and Kadhim [13] tested sixteen reinforced concrete double corbels to investigate the effect of using composite materials CFRP as strengthening or repairing material for reinforced concrete corbels and its effect on load-carrying capacity and behavior of corbels. Eleven of these corbels were strengthened by various schemes of CFRP strips, and three were repaired with damage ratios of (0, 35, and 70) %. The results showed an increase in ultimate load with a percentage reaching (43) % and an increase in cracking load to about (46) % for inclined full wrapping. CFRP strips were an effective technique for strengthening reinforced concrete corbels in this situation. Sayhood et al. [14] used twenty double-sided reinforced concrete corbels for their tests. Six of them were subjected to monotonic loads, and fourteen were subjected to non-reversed repeated loads to see if the external strengthening with CFRP strips could enhance the load-carrying capability of specimens. The results showed that strengthening delayed the first crack, increasing the cracking and failure loads and the ultimate deflection. In addition, the inclined strengthening roughly showed the best results and was economically recommended. Abdulrahman et al. [15] cast and tested seventeen double-corbels under vertical load to investigate the behavior and strength of high-strength reinforced concrete corbels strengthened with various strengthening techniques, including externally bonded CFRP fabric sheets and plates with various patterns, internal strengthening with geogrids, near surface mounted (NSM)-CFRP bars, internal CFRP bars reinforcement, and steel fiber addition. The experimental program was divided into two parts. The first included three pilot specimens tested to see how the shear span to effective depth (a/d) ratio affected the specimen strength. The second included fourteen strengthened reinforced concrete corbels using various strengthening techniques to see their efficiency in improving specimen strength. The results showed that all types of strengthening techniques increased the corbel's ultimate strength while decreasing the shear span to an effective depth (a/d) ratio, besides considerably improving load-carrying capacity. The diagonal splitting failure was the failure mode for all corbels.

2.PROBLEM STATEMENT

Although some studies of corbels have focused separately on strengthening it with externally bounded technique and separately on subjecting it to monotonic and repeated loads, none of them have simultaneously investigated the strengthening by externally bounded CFRP strips subjected to monotonic and repeated (constant and incremental) loads in corbels. Therefore, this study will investigate that.

3.MATERIALS AND SPECIMEN PROPORTIONS

The following is a summary of the materials used and their properties:

- **Cement**: Ordinary Portland cement (Type I) that meets the IQS No.5 requirements [16].
- **Fine Aggregate**: River sand with a maximum size of (4.75) mm and fineness modulus (F.M=2.62) that meets the IQS NO.45 requirements [17].
- **Coarse Aggregate**: River gravel with a maximum size of (12.5) mm with a rounded partial shape that meets the IQS No.45 requirements [17].

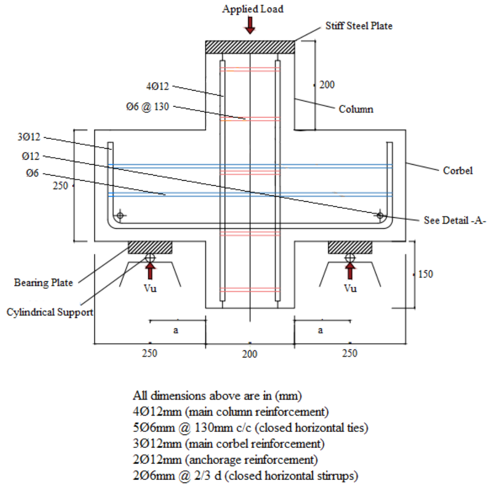
Table 1 shows the mix proportions (by weight) used in this work according to ACI 211.1 [18].

Table 1 Mix Proportions (by Weight).

Material	W/C	W	C	F.A	C.A
Proportion (kg/m3)	0.454	172	379	797	910

- **Strengthening Material**: Carbon Fiber Reinforced Polymers CFRP Strips (Sika Wrap®-300 C). A woven black unidirectional carbon fiber fabric was used for the structural external strengthening of corbels in this work.
- **Adhesive Material**: Epoxy (Sikadur®-330) consisted of two components; compound A (white color) and compound B (light grey color), recommended by CFRP specification for bonding CFRP strips with a thickness of (0.167) mm to the concrete surface.
- **Steel Reinforcement**: Deformed steel bars were used with a diameter of (12) mm for column reinforcement, main (tension) reinforcement, and crossbar for corbels, and (6) mm as tie bars for column and secondary (shear) reinforcement for corbels that meet the ASTM A615 requirements [19].

The column's dimensions were (200×600×150) mm, supporting two corbels on opposite sides of (250×250×150) mm. The shape, dimensions, reinforcement of the corbel specimen, the details of the welded crossbar, the loading technique, and the test setup are shown in Figs. 1 and 2.



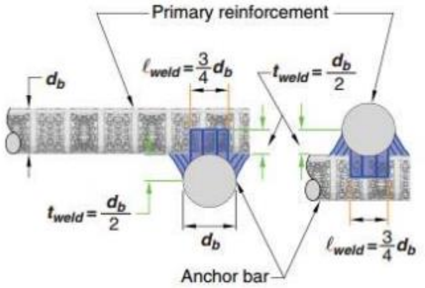


Fig. 1 Shape, Dimensions, Reinforcement of Corbel Specimen, and Details of the Welded Crossbar.

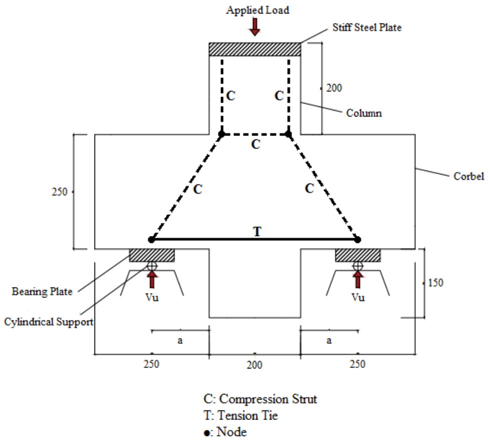


Fig. 2 Loading Technique and the Test Setup.

4.EXPERIMENTAL PROGRAM

The effect of four main parameters has been investigated in this work:

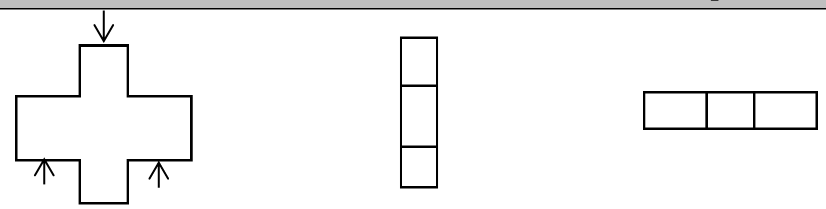
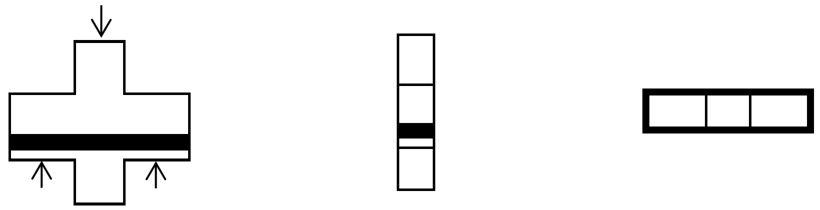
1) Type of Strengthening Patterns (Horizontal and Inclined).
2) The Number of Horizontal Patterns (One and Two).
3) Type of Applied Loads (Monotonic and Repeated).
4) Type of Repeated Loads (Constant and Incremental).

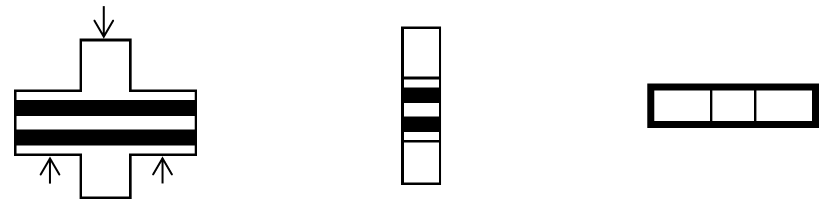
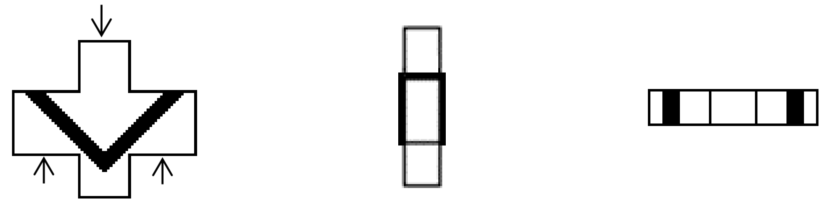
The experimental program included the casting and testing of twelve double-concrete corbels to investigate the behavior and strength of the corbels subjected to monotonic and repeated loads, nine of them were strengthened with CFRP strips using different patterns, while the others were left un-strengthened as control corbels. All specimens have been kept constant for corbel and column dimensions besides the main and secondary reinforcement. The details of corbels used in this work and their variables and strengthening are shown in Tables 2 and 3, respectively.

Table 2 Details of Concrete Corbels and their Variables.

Corbel Designation	Bonding Technique	Bonding Orientation	Number of Strips	Applied Loads	Load Variables
CCM	control corbel (un-strengthened)			monotonic	ultimate load
CCRc	control corbel (un-strengthened)			repeated-constant	60 % of the ultimate load at 5 cycles
CCRi	control corbel (un-strengthened)			repeated-incremental	20, 40, 60, and 80 % of the ultimate load at 5 cycles
CWH1M	fully wrapped	horizontal	one	monotonic	ultimate load
CWH1Rc	fully wrapped	horizontal	one	repeated-constant	60 % of the ultimate load at 5 cycles
CWH1Ri	fully wrapped	horizontal	one	repeated-incremental	20, 40, 60, and 80 % of the ultimate load at 5 cycles
CWH2M	fully wrapped	horizontal	two	monotonic	ultimate load
CWH2Rc	fully wrapped	horizontal	two	repeated-constant	60 % of the ultimate load at 5 cycles
CWH2Ri	fully wrapped	horizontal	two	repeated-incremental	20, 40, 60, and 80 % of the ultimate load at 5 cycles
CWIM	fully wrapped	inclined	one	monotonic	ultimate load
CWIRc	fully wrapped	inclined	one	repeated-constant	60 % of the ultimate load at 5 cycles
CWIRi	fully wrapped	inclined	one	repeated-incremental	20, 40, 60, and 80 % of the ultimate load at 5 cycles

Table 3 Details of Concrete Corbels and their Strengthening.

Corbel designation	Front view	Side view	Top view
CCM **CCRc** **CCRi**			
CWH1M **CWH1Rc** **CWH1Ri**			

CWH2M CWH2Rc CWH2Ri	
CWIM CWIRc CWIRi	

5.STRENGTHENING DETAILS

The strengthening details include the following:

- **The CFRP Strips** were cut into the required dimensions with a width of (50) mm and different lengths. In one of the specimens, one strip was placed in a box shape to make a horizontal strengthening; in a second specimen, two strips were placed in a box shape to make two horizontal strengthening (40) mm between them. In a third specimen, one strip was placed in a V shape to make an inclined strengthening at an angle of (45°) perpendicular to the shear cracks expected for the inclined shear forces to ensure the corbel's strengthening against these forces.
- **The Epoxy** (made up of two components) was mixed in a 4:1 weight ratio for about (2) minutes to obtain a uniform gray color.

6.TESTING PROCEDURE

The testing procedure by Hydraulic Universal Testing Machine (SANS) is as follows:

1) All corbels (on the machine) were in an inverted position and simply supported on both ends using a stiff steel frame.

2) To avoid concrete local failure, two steel bearing plates were used at the supports and one plate at the loading point.

3) The loading system contains a hydraulic jack that applies a load to the top column and divides it into two equal vertical loads at the supports applied to the corbels.

4) At testing, the load was gradually increased and recorded with deflection, first crack, and other cracks propagation up to failure:

- **a)** For monotonic load, four corbels were loaded up to failure in one cycle.
- **b)** For repeated-constant load, four corbels were subjected to five cycles of loading. Each load value was equal to (60) % of the ultimate load of the corresponding corbels that tested monotonically, and then those specimens were loaded up to failure, as shown in Fig. 3.

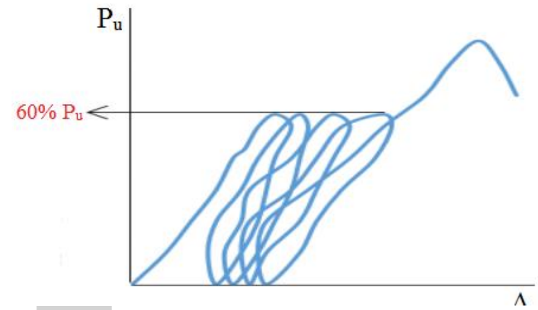


Fig. 3 Repeated-Constant Load Protocol.

- **c)** For repeated-incremental load, four corbels were subjected to five cycles of loading. The load value of each was equal to (20, 40, 60, and 80) % of the ultimate load of the corresponding corbels that tested monotonically, and then those specimens were loaded up to failure, as shown in Fig. 4.

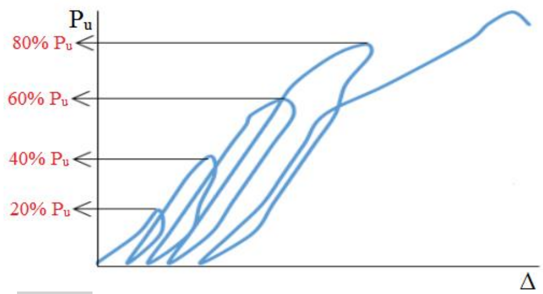


Fig. 4 Repeated-Incremental Load Protocol.

5) The applied load was measured using a load cell placed on the column's top face, and the deflection was measured using a longitudinal variable deformation transformation (LVDT) attached to the bottom face of the column. The data from the test was collected using a data logger, i.e., load and deflection.

Figs. 5 (a, b, c, d) show the testing procedures in the laboratory.

(a) Load Cell. (b) Simply Support. (c) LVDT. (d) Corbel Specimen in an Inverted Position.

Fig. 5 Testing of Specimens.

7.MECHANICAL PROPERTIES OF CONCRETE

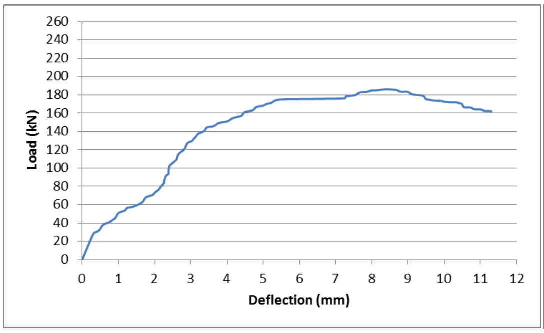
Table 4 shows the results of the control specimens' mechanical properties, which were tested at the same age as corbel testing. The control specimens' mechanical properties included testing of three cubes (100×100×100) mm in determining the compressive strength (f_{cu}) according to BS 1881-116 [20] and one cylinder (150×300) mm to determine the splitting tensile strength (f_t) according to ASTM C496 [21], where each value in this table represents the average values of specimens' results.

Table 4 Mechanical Properties of Concrete.

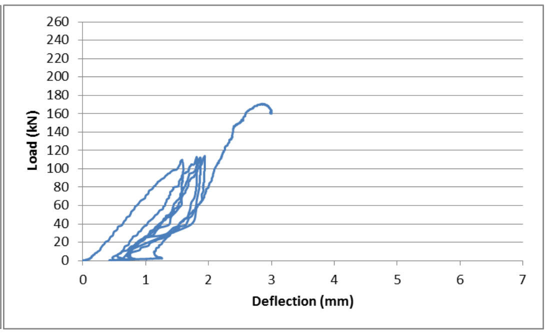
Cubic Compressive Strength (f_{cu}) (MPa)	Splitting Tensile Strength (f_t) (MPa)
37.04	4.09

8.LOAD-DEFLECTION RELATIONSHIP

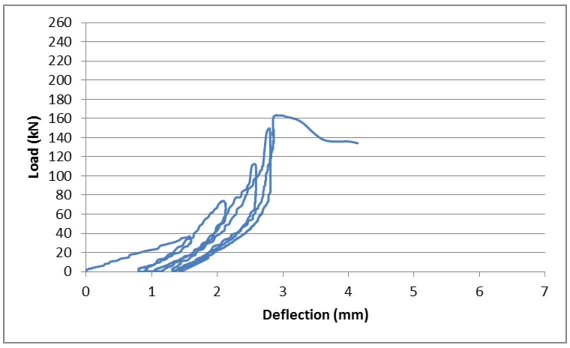
Figs. 6-9 show the load versus deflection relationships for all tested specimens under monotonic and repeated loads at all stages of loading up to failure. Those relationships were dependent on the strengthening and loading types. Generally, each load-deflection curve starts as a linear form (elastic behavior) with a constant slope. Then the curve's slope begins to change, which denotes the appearance of the first crack in the corbel. After the first crack appearance, the load-deflection curve takes a nonlinear form and starts to take a curvature path which means there is an increase in ductility. The load-deflection relationships for control corbels that were un-strengthened and subjected to monotonic and repeated loading (CCM, CCRc, and CCRi specimens) are shown in Fig. 6. The load-deflection relationships for corbels that were strengthened with CFRP strips and subjected to monotonic and repeated loading (CWH1M, CWH1Rc, CWH1Ri, CWH2M, CWH2Rc, CWH2Ri, CWIM, CWIRc, and CWIRi specimens) are shown in Figs. 7-9.



(a)

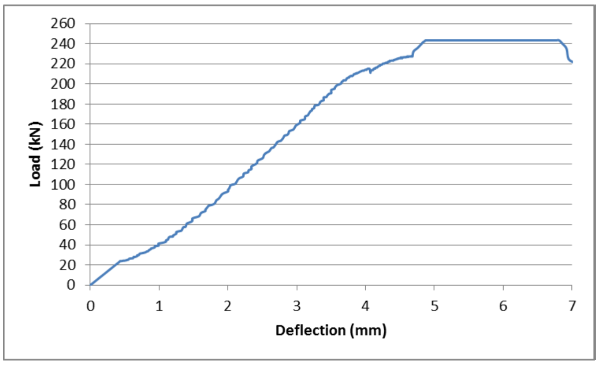


(b)

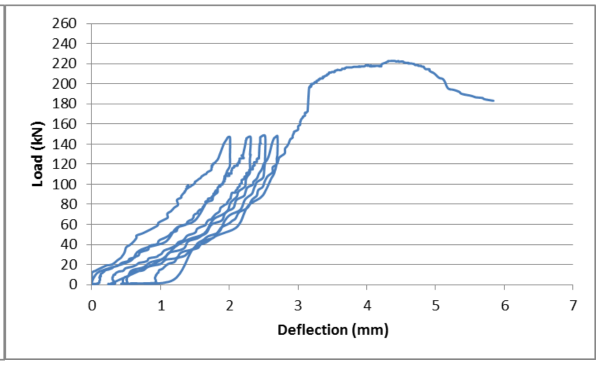


(c)

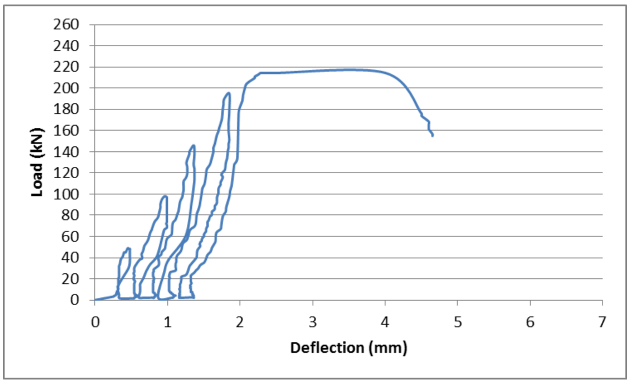
Fig. 6 Load-Deflection Relationship for Specimens (a) CCM, (b) CCRc, and (c) CCRi.



(a)

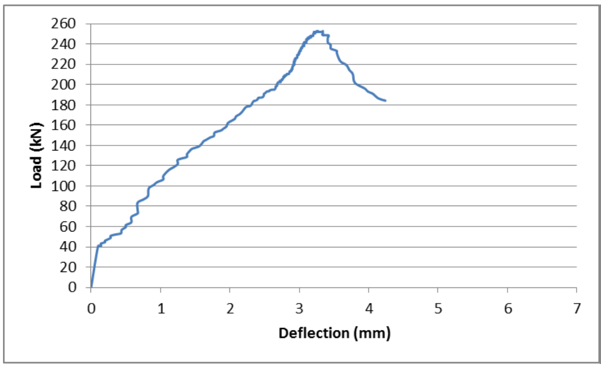


(b)

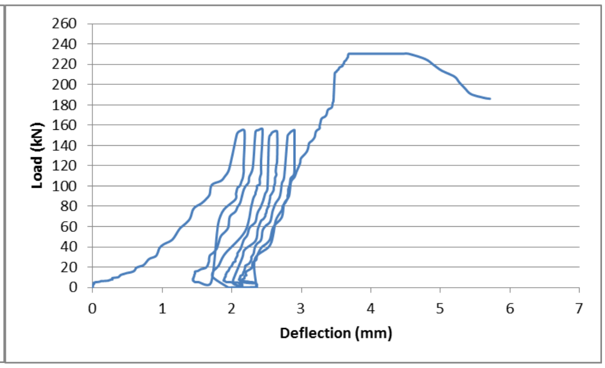


(c)

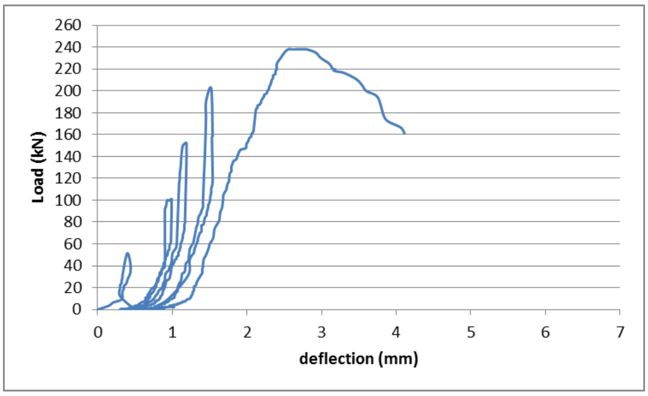
Fig. 7 Load-Deflection Relationship for Specimens (a) CWH1M, (b) CWH1Rc, and (c) CWH1Ri.



(a)

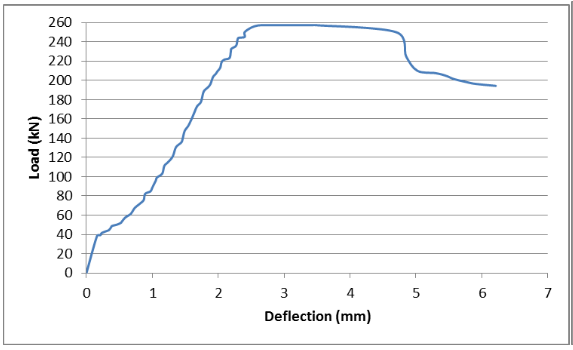


(b)

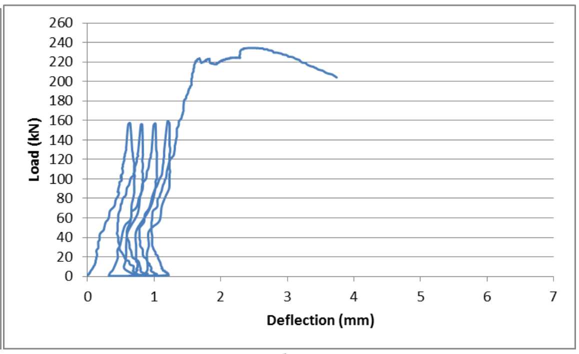


(c)

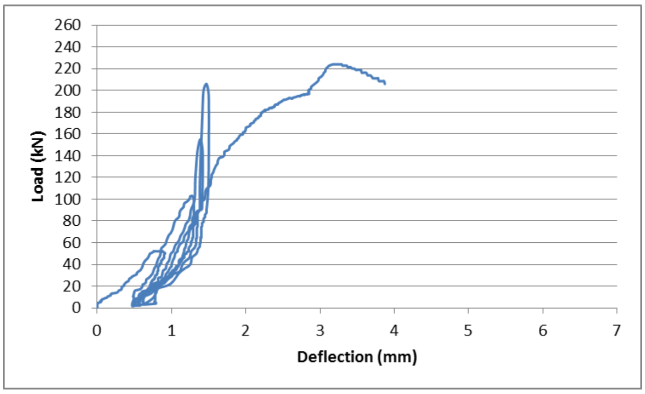
Fig. 8 Load-Deflection Relationship for Specimens (a) CWH2M, (b) CWH2Rc, and (c) CWH2Ri.



(a)



(b)



(c)

Fig. 9 Load-Deflection Relationship for Specimens (a) CWIM, (b) CWIRc, and (c) CWIRi.

9.EFFECT OF PARAMETERS

9.1.Effect of Loading Type

The effect of loading type, i.e., monotonic, repeated-constant, and repeated-incremental, on the ultimate load capacity is shown in Table5. Corbels subjected to monotonic loading are considered a reference for similar corbels subjected to repeated loading (as a percent of their monotonic load corbels).

Table 5 Effect of Loading Type.

Corbel Designation	P_u (kN)	Increasing of P_u (%)	Increasing of P_u (%)	Increasing of P_u (%)	Δu (mm)	Mode
CCM	186	-			8.35	D.S
CWH1M	244	31.18			4.87	D.S
CWH2M	253	36.02			3.25	D.S
CWIM	258	38.71			2.7	D.S
CCRc	170		-		2.83	D.S
CWH1Rc	223		31.18		4.31	D.S
CWH2Rc	231		35.88		3.68	D.S
CWIRc	235		38.24		2.41	D.S
CCRi	164			-	2.9	D.S
CWH1Ri	215			31.10	2.28	D.S
CWH2Ri	238			45.12	2.55	D.S
CWIRi	224			36.59	3.17	D.S

* P_u refers to ultimate load, Δu refers to deflection at ultimate load, and D.S refers to diagonal splitting failure.

The following can be observed from Table 5:

1) When the loading type was **monotonic**, the increase in the ultimate loads for CWH1M, CWH2M, and CWIM specimens were about 31.18, 36.02, and 38.71 %, respectively, compared to the control corbel (CCM specimen).
2) When the loading type was **repeated-constant**, the increase in the ultimate loads for CWH1Rc, CWH2Rc, and CWIRc specimens were about 31.18, 35.88, and 38.24 %, respectively, compared to the control corbel (CCRc specimen).
3) When the loading type was **repeated-incremental**, the increase in the ultimate loads for CWH1Ri, CWH2Ri, and CWIRi specimens were about 31.10, 45.12, and 36.59 %, respectively, compared to the control corbel (CCRi specimen).

Generally,

- The ultimate loads of corbels subjected to repeated loading were lower than those of identical corbels subjected to monotonic loading.
- The ultimate loads of corbels subjected to repeated-incremental loading were lower

than those of identical corbels subjected to repeated-constant loading. Except for the CWH2Ri specimen, it was higher than the CWH2Rc specimen in the ultimate load.

Due to the loading-unloading processes that caused stress fluctuation, deformation accumulation, and more damage in concrete, applying five cycles of repeated loads to corbel specimens decreased the ultimate load and ultimate deflection compared to similar specimens under monotonic loads.

9.2. Effect of Strengthening Type

The effect of strengthening type, i.e., horizontal-one strip, horizontal-two strips, and inclined strip, on the ultimate load capacity is shown in Table 6.

Table 6 Effect of Strengthening Type.

Corbel designation	P_u (kN)	Increasing of P_u (%)	Increasing of P_u (%)	Increasing of P_u (%)	Δu (mm)	Mode
CCM	186	-			8.35	D.S
CCRc	170	-			2.83	D.S
CCRi	164	-			2.9	D.S
CWH1M	244	31.18	-		4.87	D.S
CWH1Rc	223	31.18	-		4.31	D.S
CWH1Ri	215	31.10	-		2.28	D.S
CWH2M	253	36.02	3.69	-	3.25	D.S
CWH2Rc	231	35.88	3.59	-	3.68	D.S
CWH2Ri	238	45.12	10.70	-	2.55	D.S
CWIM	258	38.71	5.74	1.98	2.7	D.S
CWIRc	235	38.24	5.38	1.73	2.41	D.S
CWIRi	224	36.59	4.19	-5.88	3.17	D.S

* P_u refers to ultimate load, Δu refers to deflection at ultimate load, and D.S refers to diagonal splitting failure.

The following can be observed from Table 6:

1) When the strengthening type was **horizontal-one strip, horizontal-two strips, and inclined strip**.
   a) The increase in ultimate loads for CWH1M, CWH1Rc, and CWH1Ri specimens were about 31.18, 31.18, and 31.10 %, respectively, compared to the control corbels (CCM, CCRc, and CCRi specimens).
   b) The increase in ultimate loads for CWH2M, CWH2Rc, and CWH2Ri specimens were about 36.02, 35.88, and 45.12 %, respectively, compared to the control corbels (CCM, CCRc, and CCRi specimens).
   c) The increase in ultimate loads for CWIM, CWIRc, and CWIRi specimens were about 38.71, 38.24, and 36.59 %, respectively, compared to the control corbels (CCM, CCRc, and CCRi specimens).
2) When the strengthening type was **horizontal-two strips and inclined strip**.
   a) The increase in ultimate loads for CWH2M, CWH2Rc, and CWH2Ri specimens were about 3.69, 3.59, and 10.70 %, respectively, compared to CWH1M, CWH1Rc, and CWH1Ri specimens.
   b) The increase in ultimate loads for CWIM, CWIRc, and CWIRi specimens were about 5.74, 5.38, and 4.19 %, respectively, compared to CWH1M, CWH1Rc, and CWH1Ri specimens.
3) When the strengthening type was an **inclined strip**.
   a) The increase in ultimate loads for CWIM and CWIRc specimens were about 1.98 and 1.73 %, respectively, compared to CWH2M and CWH2Rc specimens.
   b) The decrease in ultimate load for the CWIRi specimen was about (5.88) % compared to the CWH2Ri specimen, demonstrating that strengthening using horizontal-two strips was more effective from the inclined strip for this specimen.

Generally,

- The ultimate loads of corbels strengthened by an inclined strip were higher than those of identical corbels strengthened by a horizontal strip. Except for the CWIRi specimen, it was lower than the CWH2Ri specimen in the ultimate load.
- The ultimate loads of corbels strengthened by horizontal-two strips were higher than those of identical corbels strengthened by horizontal-one strip.

Due to the CFRP strips' participation in resisting the diagonal stresses that often control the failure, using CFRP strengthening resulted in reducing the deflection values to a certain level by increasing the load capacity and resistance to deformation. This increase in load capacity could be due to the increased stiffness and crack restriction caused by using CFRP strips as an external strengthening material and immersing it in epoxy.

10. STIFFNESS (K)

According to ASTM C1018 [22], stiffness is the load required to produce unit deformation in the member; it can be calculated by dividing (45) % of the ultimate load of any member by the corresponding deflection. Table 7 shows the stiffness of corbel specimens that were tested.

Table 7 Stiffness (K).

Corbel Designation	P_u (kN)	45 % P_u (kN)	Δ at 45 % P_u (mm)	Stiffness (kN/ mm)
CCM	186	84	2.26	37.17
CCRc	170	77	1.96	39.29
CCRi	164	74	2.67	27.72
CWH1M	244	110	2.23	49.33
CWH1Rc	223	100	2.5	40
CWH1Ri	215	97	1.85	52.43
CWH2M	253	114	1.12	101.79
CWH2Rc	231	104	2.85	36.49
CWH2Ri	238	107	1.7	62.94
CWIM	258	116	1.23	94.31
CWIRc	235	106	1.19	89.08
CWIRi	224	101	1.44	70.14

* Un-strengthened corbels considered reference specimens (CCM, CCRc, and CCRi) for different types of loading.

The following can be observed from Table 7:

1) At most, the stiffness of corbels subjected to repeated loading was lower than that of corbels subjected to monotonic loading because the repeated loading decreased the ultimate load and ultimate deflection, resulting in a lower stiffness. The lowest corbel's stiffness was for the CCRi specimen, which was un-strengthened and subjected to repeated-incremental loading.
2) At most, the stiffness of corbels strengthened with CFRP strips was higher than that of un-strengthened corbels because using CFRP strips increased the ultimate load and decreased the ultimate deflection, resulting in a higher stiffness. The highest corbel's stiffness was for the CWH2M specimen, which was strengthened by horizontal-two strips and subjected to monotonic loading.

11.FAILURE MODE

The specimens considered control corbels, i.e., CCM, CCRc, and CCRi, had diagonal cracks that widened and propagated upward with increasing loading. Therefore, the failure modes appeared as a diagonal splitting, as shown in Fig. 10.

(a)

(b)

(c)

Fig. 10 Failure Mode for Specimens (a) CCM, (b) CCRc, and (c) CCRi.

For specimens that were strengthened with externally bounded CFRP strips tested under monotonic and repeated loading, i.e., CWH1M, CWH1Rc, CWH1Ri, CWH2M, CWH2Rc, CWH2Ri, CWIM, CWIRc, and CWIRi, had a mix of diagonal and vertical cracks, as follow:

- These cracks widened and caused de-bonding of the lower CFRP strip at the left support region for CWH1M, CWH1Rc, and CWH1Ri specimens.
- These cracks widened and caused de-bonding of the two CFRP strips at the left support region for CWH2M and CWH2Rc

specimens and at the right support region for the CWH2Ri specimen.

- These cracks widened and caused de-bonding of the inclined CFRP strip at the right support region for the CWIM specimen and caused de-bonding with rupture of the inclined CFRP strip at the left support region for CWIRc and CWIRi specimens.

Therefore, the failure modes appeared as a diagonal splitting, as shown in Figs. 11-13, with CFRP de-bonding from the concrete surface at the cracks' region.

(a) (b)

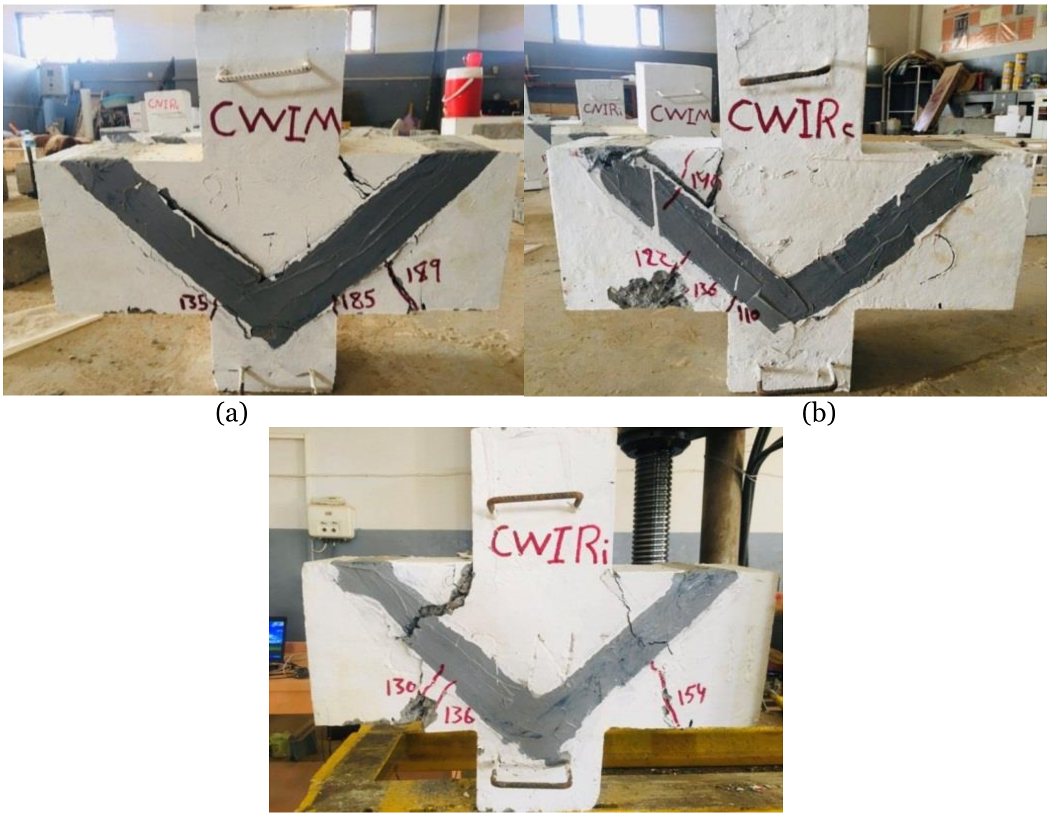
(c)

Fig. 11 Failure Mode for Specimens (a) CWH1M, (b) CWH1Rc, and (c) CWH1Ri.

(a) (b)

(c)

Fig. 12 Failure Mode for Specimens (a) CWH2M, (b) CWH2Rc, and (c) CWH2Ri.



(a) (b)

(c)

Fig. 13 Failure Mode for Specimens (a) CWIM, (b) CWIRc, and (c) CWIRi.

12.CONCLUSION

The following conclusions are obtained from the experimental results of the tested corbels:

1) Corbels subjected to repeated loading failed in a more ductile manner than those subjected to monotonic loading.
2) Both types of repeated loads, i.e., constant and incremental, affected the ultimate load capacity of corbels, where a reduction occurred in ultimate load and ultimate deflection for corbels subjected to five cycles of repeated loading compared to those subjected to monotonic loading.
3) The repeated-incremental loading significantly affected the reduction in ultimate load and ultimate deflection of corbels compared to those subjected to repeated-constant loading.
4) For corbels strengthened by externally bounded CFRP strips under any type of applied loads, the ultimate load significantly increased, while the ultimate deflection decreased compared to those un-strengthened at the same applied load.
5) The location, orientation, and number of CFRP strips were essential in enhancing the stiffness, cracking and ultimate loads, and their corresponding deflections. Therefore, it was found that the strengthening pattern by inclined wrapped as V shape showed better results for the specimen than strengthened by horizontal fully wrapped as box shape and un-strengthened at all.
6) For the strengthening effect, when the number of horizontal strips increased from one to two strips, the ultimate loads increased by (35.88-45.12) % compared to those un-strengthened. When the orientation of strips changed from horizontal to inclined strips, the ultimate loads increased by (36.59-38.71) % compared to those un-strengthened.
7) The strengthening effect in horizontal strips significantly depended on the CFRP strips' location. CFRP strips applied in the tension zone of the corbel specimen were affected more than those applied near or in the compression zone. As a result, applying the first strip increased the ultimate load capacity by (31.10-31.18) %; however, applying the second strip increased the ultimate load capacity by (35.88-45.12) %.
8) The de-bonding of the CFRP strips was sudden and had a brittle nature. So, the only warning of the de-bonding was a few sounds that indicated high forces in the CFRP strips. Therefore, using CFRP strips reduced the corbels' ductility.
9) The repeated loading negatively affected the corbels' stiffness, while CFRP strengthening improved the stiffness of tested corbels.

REFERENCES

[1] ACI Committee 318M-19. Building Code Requirements for Structural Concrete and Commentary (ACI 318M-19). American Concrete Institute, 2019.

[2] Kriz LB, Raths CH. **Connections in Precast Concrete Structures-Strength of Corbels**. *PCI Journal* 1965; **10**(1): 16-61.

[3] Meier U. **Repair Using Advanced Composites.** *International Conference: Composite Construction-Conventional and Innovative* 1997; Innsbruck, Austria. IABSE: p. 113-123.

[4] Alshadidi RM, Hassan HF, Mohammed MH. **Shear Behavior of High Strength Concrete Beams Reinforced with GFRP Bars and Strengthened by CFRP Sheets**. *Journal of Engineering and Development* 2016; **20**(1): 102-117.

[5] Mohammed DH. *Behavior of Reinforced Concrete Beams Strengthened by CFRP in Flexure*. Ph.D. Thesis. University of Technology; Baghdad, Iraq: 2007.

[6] David E, Djelal C, Bodin FB. **Repair and Strengthening of Reinforced Concrete Beams Using Composite Materials**. *2nd International PhD Symposium in Civil Engineering* 1998; Budapest, Hungary.

[7] Raoof SM, Koutas LN, Bournas DA. **Textile-Reinforced Mortar (TRM) Versus Fibre-Reinforced Polymers (FRP) in Flexural Strengthening of RC Beams**. *Construction and Building Materials* 2017; **151**: 279-291.

[8] Alali SSH, Abdulrahman MB, Tayeh BA. **Response of Reinforced Concrete Tapered Beams Strengthened Using NSM-CFRP Laminates**. *Tikrit Journal of Engineering Sciences* 2022; **29**(1): 99-110.

[9] Ashour SA, Hasanain GS, Wafa FF. **Shear Behavior of High Strength Fiber Reinforced Concrete Beam**. *ACI Structural Journal* 1992; **89**(2): 176-184.

[10] Almashaykhi M, Alsubari B, Abdulrahman MB, Hussein AA. **Punching Strength of Reactive Powder Reinforced Concrete Flat Slabs**. *Tikrit Journal of Engineering Sciences* 2021; **28**(3): 35-47.

[11] Jasim IKh, Abdulrahman MB, Jomaa'h MM, Alsubari B, Abdulaali HS, Alqawzai Sh. **Torsional Behavior of RC Beams with Transverse Openings Strengthened by Near Surface Mounted-Steel Wire Rope Subjected to Repeated Loading**. *Tikrit Journal of Engineering Sciences* 2022; **29**(4): 79-89.

[12] Mohamad-Ali AA, Attiya MA. **Experimental Behavior of Reinforced Concrete Corbels Strengthened with Carbon Fibre Reinforced Polymer Strips**. *Basrah Journal for Engineering Science* 2012; **12**: 31-45.

[13] Shadhan KK, Kadhim MMM. **Use of CFRP Laminates for Strengthening of Reinforced Concrete Corbels**. *International Journal of Civil Engineering and Technology* 2015; **6**(11): 11-20.

[14] Sayhood EK, Hassan QA, Yassin LAGh. **Enhancement in the Load-Carrying Capacity of Reinforced Concrete Corbels Strengthened with CFRP Strips Under Monotonic or Repeated Loads**. *Engineering and Technology Journal* 2016; **34**(14): 2705-2719.

[15] Abdulrahman MB, Salih ShA, Abduljabbar RJ. **The Assessment of Using CFRP to Enhance the Behavior of High Strength Reinforced Concrete Corbels**. *Tikrit Journal of Engineering Sciences* 2021; **28**(1): 71-83.

[16] Iraqi standard specifications No.5. **Portland Cement**. The Iraqi Central Organization for Standardization and Quality Control, Planning Council, Baghdad, Iraq: 1984 (in Arabic).

[17] Iraqi standard specifications No.45. **Aggregates from Natural Sources for Concrete and Building Construction**. The Iraqi Central Organization for Standardization and Quality Control, Planning Council, Baghdad, Iraq: 1984 (in Arabic).

[18] ACI Committee 211.1-91. **Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)**. American Concrete Institute, 1991.

[19] ASTM A615/A615M-15a. **Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement**. American Society for Testing and Materials, 2018.

[20] BS 1881-116. **Method of Determination of Compressive Strength of Concrete Cubs**. British Standards Institution, 1983.

[21] ASTM C496/C496M. **Splitting Tensile Strength of Cylindrical Concrete Specimens**. American Society for Testing and Materials, 2017.

[22] ASTM C1018. **Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete**. American Society for Testing and Materials, 2018.