EXPERIMENTAL BEHAVIOUR OF REINFORCED CONCRETE CORBELS STRENGTHENED WITH CARBON FIBRE REINFORCED POLYMER STRIPS

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ABSTRACT

This research is devoted to investigate the effect of Carbon Fibre Reinforced Polymer (CFRP) strips on the behaviour and load carrying capacity of strengthened and repaired reinforced concrete corbels. Experimental investigation were carried. The experimental program variables include location, direction, amount of CFRP strips and effect of shear span to effective depth (a/d) ratio on the behaviour of strengthened corbels. All corbels had the same dimensions and flexural reinforcement and they were without horizontal shear steel reinforcement. The experimental results obtained from the adopted strengthening and repairing CFRP techniques showed a significant improvement in the behaviour and carrying capacity of the tested corbels. An increase of about (44.5 - 60) % in the ultimate load has been obtained for specimens strengthening by inclined technique compared to the ultimate load of control corbel and (14.7 - 31.2)% for specimens strengthening horizontal technique. For corbels repaired with CFRP strips, an increase of (56%) with respect to the ultimate load of control corbel is achieved. Also the strengthened corbels show stiffer load deflection response than corresponding control corbels (unstrengthened corbels).

سلوك الكتائف الخرسانية المسلحة المقواة بشرائح البوليمر المسلحة بألياف الكاربون

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الخلاصة

إن الهدف من هذا البحث هو التحري عن سلوك وسعة تحمل الكتائف الخرسانية المسلحة المقواة والمعالجة بشرائح ألياف الكاربون (CFRP) في مناطق القص. تضمنت الدراسة تهيئة وفحص ثلاثون عينة من الكتائف الخرسانية المسلحة مقسمة إلى أربعة مجاميع. مجموعتان منها مقواة بشرائح ألياف الكاربون بشكل أفقي بينما كانت المجموعتان الأخريان مقواة بشكل مائل بشرائح الكاربون. الدراسة العملية تضمنت عدة متغيرات منها موقع و اتجاه و كمية شرائح ألياف الكاربون و نسبة فضاء القص إلى العمق الفعال (a/d) تؤثر جميعها على سلوك الكتائف المقواة. جميع الكتائف كان لها نفس الأبعاد وقضبان حديد الشد ولم تحتوي على اية قضبان حديد قص. أظهرت النتائج المختبرية إن استخدام اسلوب التقوية بشرائح ألياف الكاربون يحسن من تصرف وسعة التحمل للكتائف الخرسانية المسلحة. وان نسبة زيادة تحمل الكتائف الخرسانية المقواة بشرائح ألياف الكاربون تراوحت بين 44.5% و 60% من مقدار تحمل الكتائف الخرسانية غير المقواة بالنسبة للكتائف المقواة بشكل مائل و 14.7 و 31.2 % بالنسبة للكتائف المقواة بشكل أفقي. أما بالنسبة للكتائف المتشققة المعالجة بشرائح ألياف الكاربون فان مقدار الزيادة في سعة التحمل كانت 56% من مقدار تحمل الكتائف الخرسانية غير المقواة. وكذلك بينت النتائج المختبرية بأن منحنيات الحمل-التشوه للكتائف الخرسانية المقواة أفضل من منحنيات الكتائف الخرسانية غير المقواة.

Key words: Corbel, Carbon Fiber, Strengthened, Nonlinear Analysis, Finite Element Analysis.

1- INTRODUCTION

Corbels, are short cantilevers with a shear span to depth ratio lower than unity, generally built monolithically with the column or wall. They have the principal function of supporting prefabricated beams or floors at building joints, allowing, at the same time, the force transmission to the supporting vertical structural members. Corbels are principally designed to resist the ultimate shear force V_u applied to them by the beam [1]. Unless special precautions are taken to avoid horizontal forces caused by shrinkage, creep (in case of prestressed beam), or temperature changes, they must also be able to resist a horizontal force. Steel plates are usually provided at the top surface of the corbel to ensure the uniform contact surface and distribute the reaction (BS 8110: Part 1: 1997)[2].

The principal failure modes for members without stirrups are:1- shear failure; 2- yielding of the principal reinforcement (flexural tension); 3- crushing of concrete strut (flexural compression); and 4- diagonal splitting [3]. All failure modes previously mentioned tend to converge into a single typology in corbels with secondary reinforcement (stirrups) called beam-shear failure. The last one is characterized by the opening of one or more diagonal cracks followed by shear failure in the compressed zone of the strut(ACI 318-08)[4].

Externally strengthening with advanced composite materials, namely, carbon fibre reinforced polymers (CFRP), represents the state-of-the-art in upgrading or rehabilitation techniques [5], fibre reinforced polymer (CFRP) laminates are becoming widely used in upgrading and rehabilitation of reinforced concrete members. The utilization of Carbon Fibre Reinforced Polymers, in the construction fields has received a special attention in the last decade . This is attested to by the extensive research activities on CFRP and resulted in a significant advancement in state of the art of the use of CFRP in the construction fields. In addition, its use in the repair and strengthen structures has become a well accepted practice (ACI Committee 440, 2002)[6].

The objective of the present study is to investigate, experimentally the behaviour of reinforced concrete corbels externally strengthened or repaired with Carbon Fibre Reinforced Polymer sheets (CFRP) in shear. The research presented in this work covers the following areas:

- Experimentally investigate the shear behaviour of reinforced concrete corbels strengthened with CFRP strips.
- Comparison of the performance of reinforced concrete corbels strengthened or repaired with CFRP sheets in shear. The main variables of the experimental work are the width, number of layers, length of layer, location and direction of CFRP sheets.
- Study the effect of shear span to depth ratio on the behaviour and load carrying capacity of strengthened corbels.
- Study the effect of the presence CFRP strips on the width of shear cracks.

2- EXPERIMENTAL PROGRAM

The primary independent variables were, width of CFRP strips, length of CFRP strips, No. of CFRP strips, strengthening direction of CFRP strips and shear span-to-depth (a/d) ratio. The response variables were load carrying capacity, load versus deflection curve, shear crack pattern, concrete strain and the tensile strain of CFRP strips. A total of thirty corbels were tested. The pertinent details are presented in Table 2.1. The three a/d ratios considered are 1.0, 0.7, and 0.5.

Table 2.1 Details of the Tested corbel.

Corbel designation	Corbel type	(a/d) Ratio	CFRP Properties	
			Horizontal strips width (mm).	Inclined strips width (mm).
CONT1	Control	0.7	_	_
CHS2	Strengthened	0.7	36.0	_
CHS3	Strengthened	0.7	18.0	_
CHS4	Strengthened	0.7	18.0	_
CIS2	Strengthened	0.7	–	36.0
CIS3	Strengthened	0.7	–	18.0
CIS4	Strengthened	0.7	–	18.0
CHSR1	Strengthened	0.7	72.0	_
CHSR2	Strengthened	0.7	36.0	_
CHSR3	Strengthened	0.7	18.0	_
CHSR4	Strengthened	0.7	18.0	_
CISR2	Strengthened	0.7	–	36.0
CISR3	Strengthened	0.7	–	18.0
CISR4	Strengthened	0.7	–	18.0
CHSFR4	Strengthened	0.7	18.0	_
CISFR2	Strengthened	0.7	–	36.0
CONT2	Control	1.0	_	_
CISR2	Strengthened	1.0	–	36.0
CONT3	Control	0.5	–	_
CISR2	Strengthened	0.5	–	36.0
CISR2	Repaired	0.7	_	36.0

2-1 Details of Specimens Geometry and Reinforcement

Dimensions of the corbels are shown in Fig.2.1. The column supporting the two corbels cantilevering on either side was 150 by 150mm in cross section and 450mm long. Corbels had cantilever projection length of 200mm, with thicknesses of 150mm at both faces of column and the free end.

Columns were reinforced with four deformed bars having a 12.7mm diameter and stirrups having a 6mm diameter placed at a pitch of 125mm. Reinforcement details for the corbels are presented in Fig.2.1. The primary reinforcement (main bars) having diameter 12.7mm, placed at the bottom of the beam with an effective cover of 25mm. Main bars were welded with cross bar of similar diameter , near the end of each corbels, to provide additional anchorage

2.2 CFRP Strengthened System

Strengthened schemes were chosen carefully based on the practical needs and the field conditions, mainly, crack pattern and practical applied in the actual and economic. In this research work, thirty corbels were strengthened with externally bonded CFRP as described below. Schematic representation of the strengthened schemes is shown in Fig. 2.2 and 2.3, twenty six of these specimens were tested with (a/d=0.7), two tested with (a/d=1.0) and two tested with (a/d=0.5). Corbels CONT1, CONT2, and CONT3 with shear span to effective ratio 1.0, 0.7,and 0.5 respectively, were kept without strengthened as shown in Fig. 2.1, they are considered as control corbels for comparison.

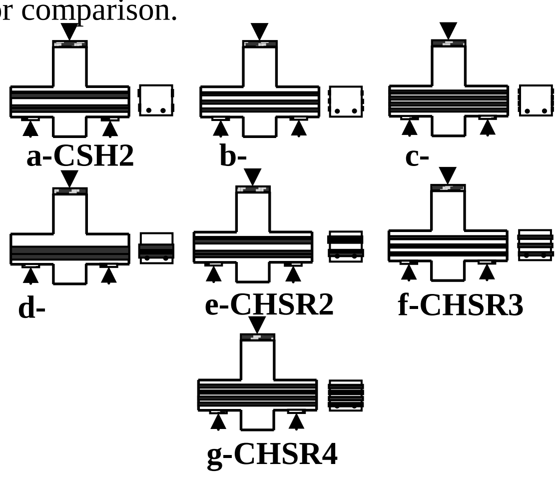


Fig. (2-1). Dimensions and Reinforcement Details.

Fig. (2-2) detail and geometry of specimens for corbel subgroup CHS and CHSR

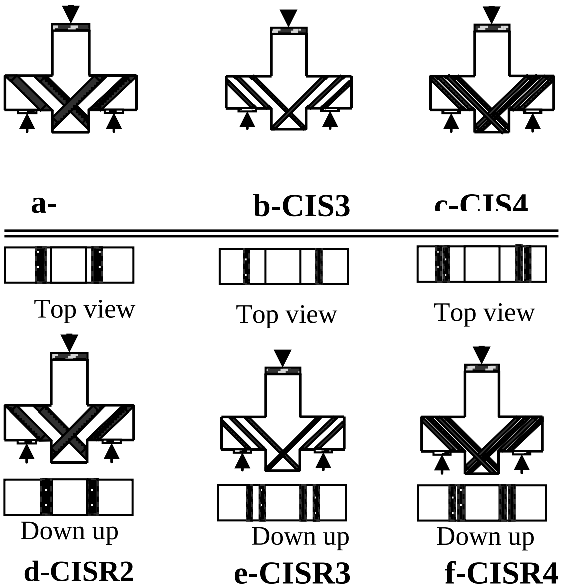


Fig.(2.3) Detail and geometry of specimens for corbel subgroup CIS and CISR

2.3 Preparation of the Specimens

Mixing was manually carried out in the Structures Laboratory of the College of Engineering at the University of Kufa. The surfaces of the pan and the mixing tools were cleaned and moistened before use. The dry ingredients were added in the following order, the coarse aggregate and fine aggregate were mixed with some of the required water for one minute. Then cement and rest of the water was added and mixing was started. The period of mixing ranged from five to seven minutes.

2.4 Mix Design

According to the specification of ACI 211.4R 93 (Neville 2000), several trial mixes were made to obtain a compressive strength of cylinder ranging between 35 and 38 MPa at 28 days. The cement content was 391 kg/m3. Water/Cement ratio was 0.52 with a slump of 90mm. A proportion by weight (1:1.95:2.24) was found to be sufficient to obtain a compressive strength of 35-38 MPa.

Three cubes were tested at date of testing the corbels to obtain the compressive strength of concrete at time of testing as shown in Table 2.2 .

Table 2.2 Compressive and tensile strength of concrete.

Beam designation	Compressive strength at time of testing (MPa) cubes*	Tensile strength at time of testing (MPa) **
CONT1and CHS2	47.57	2.11
CHS3 and CHS4	46.46	2.52
CHSR2and CHSR3	46.07	2.55
CHSR4 and CIS2	43.16	2.35
CIS3 and CIS4	45.28	2.51
CISR2 and CISR3	46.31	2.62
CISR2 and CISFR2	43.45	2.34
CHSR4 and CISR2$_1$	42.90	2.70
CISR2$_{rep}$an dCISR2$_{.5}$	46.68	2.59
CONT2$_1$an dCONT3$_{.5}$	45.72	2.50
CHSR1	43.00	2.43

*…..…Average of three cubes
**…..Average of three cylinders

2.5 Bonding of CFRP to Reinforced Concrete

Prior to bonding CFRP to the corbel, concrete surface at all faces of the corbel sides was cleaned from lousy materials by a scraper machine. Also the four corners of the specimen were chamfered at a radius R=15 mm to reduce the decrease in strength that would arise due to sheet bending at the corners, then the location of CFRP strips were washed by water and dried before installation.

As a first step in the CFRP installation, the two-parts Sikadure-330 of (Comp A and Comp B) were mixed in 4:1 proportion by using electrical mixer until the color was gray. The epoxy mixer has been applied to the surface of concrete at location of CFRP strips to fill the cavities. Also the epoxy mixer poured on surface of CFRP strips and these strips were applied to the surface of concrete.

Fig.2.4 represents specimens after removing of lousy materials and applied CFRP and painted.

a) after removing lousy

b) specimens after applied CFRP strips

c) specimens after painting

Fig.(2.4) General view of the tested corbels

2.6 Description of Universal Testing Machine

The universal testing machine used for testing the reinforced concrete corbels consists of a vertical system of applied loads and a hydraulic system of measuring the applied loads.

2.6-1 Vertical System of Applied Load

The system of applying the loads includes two vertical steel columns of large section with (3*m*) height and it is constructed on strong concrete floor at ground base with hydraulic system which enables one to determine the location and type of the applied load. Fig.2.5 shows the vertical system of applied loads.

2.6.2 Hydraulic System for Measuring the Applied Load

It is a steel box that contains a system of electrical control for operating the applied load by hydraulic pipes linked with the loading system as previously mentioned. It includes a main gauge with three divisions, with a maximum capacity of(2000 kN) Fig. 2.5. This part operates continuously during testing stages of the sample until failure.

Fig.(2.

ine.

2.7 Testing Procedure

Corbel specimens were painted and marked, Demec discs were fixed on marking location. The corbels were then loaded as shown in Fig.2.6. vertical load on the corbel was applied by The 2000-kN hydraulic testing machine available at Al-Kuffa University Laboratory which is shown in Fig.2.5. Bearing plates of 150*mm* x150*mm* were used at loading point and at supports to avoid local crushing of concrete. Details of the machine and frames used for testing the corbels are shown in Fig.2.7.

Fig (2.6) Details of the machine and frames used for testing corbels.

2.8 Instrumentation

At each test, deflection, width of shear crack, concrete *strain*, strain in inclined and horizontal CFRP strips and ultimate load were recorded. The tools, which were used during the tests, are as follows

1- Dial gauge (reading accuracy of 0.01mm) to calculate deflection.
2- Mechanical extensometer to calculate strains in concrete and CFRP strips.
3- Zooming in tool to measured shear crack width.
4- Demec points for calculating strains.
Fig 2.7 shows the tools used during testing the corbels (dial gauge, demec points and mechanical extensometer).

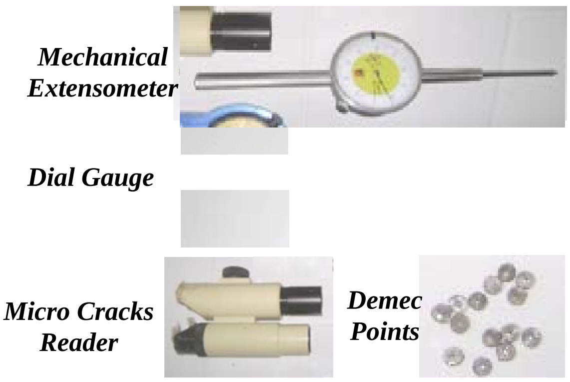


Fig.(2.7) Tools used for the tested corbels.

The strain in each horizontal CFRP strip was measured at regions located between demec points. Also the strain in each inclined CFRP strips was measured

2.9 Testing Procedure of the Specimens

All the tested corbels were white painted to facilitate detection of cracks. For each the tested corbels, the load was applied in small increments. Each increment of loading was 10*kN* up to the ultimate load. At each increment, readings were manually recorded, while the width of crack, concrete strain and strain in CFRP strips were recorded at selected a load level of 20 or 30 *kN*. The same test procedure was followed for all corbels. All of the specimens were tested under monotonically increasing load up to failure. After failure, the cracks were outlined by thick dark blue marker pen and the corbel was photographed.

3-EXPERIMENTAL RESULTS

The strengthened corbels tested in this study were divided into four groups. The cracking load, ultimate load and deflections at cracking and ultimate stages are shown in Table 3.1. The same mode of failure occurs for all corbels. This mode was a diagonal shear crack causes rupture of all CFRP strips located in the shear zone at ultimate load level.

Table 3.1 Experimental Results of the Tested Corbels.

corbel designation	(a/d) ratio	Total applied load (kN)			Mid-span deflection (mm)		Percentage increase in ultimate load with respect to reference corbel
		$P_c(f)$ *	$P_c(s)$ **	P_u	$\Delta_{c(f)}$	Δ_u	
CONT1	0.7	50	120	$292^{\dagger}$	0.4	3.29	-
CHS2	0.7	55	130	$335^{\dagger}$	0.11	2.75	14.726%
CHS3	0.7	50	150	$370^{\dagger}$	0.09	3.38	26.712%
CHS4	0.7	65	130	347	0.13	3.58	18.835%
CHSR2	0.7	60	130	$340^{\dagger}$	0.06	2.92	16.438%
CHSR3	0.7	60	130	$383^{\dagger}$	0.08	3.5	31.164%
CHSR4	0.7	60	130	$353^{\dagger}$	0.08	3.62	20.890%
CHSR1	0.7	60	160	348	0.5	2.42	19.178%
CHSFR4	0.7	65	200	356	0.69	2.84	21.917%
CIS2	0.7	75	200	$430^{\dagger}$	0.66	3.45	47.26%

CIS3	0.7	70	200	422†	0.64	3.95	44.52%
CIS4	0.7	80	200	425	0.66	3.97	45.54%
CISR2	0.7	75	200	467†	0.71	3.25	59.93%
CISR3	0.7	70	150	435	0.47	3.85	48.97%
CISR4	0.7	75	140	447	0.36	4.3	53.082%
CISFR4	0.7	85	160	454	0.39	3.3	55.479%
CISR2 repair	0.7			458			56.68%
CONT2	1.0	40	100	235	0.7	3.56	-
CISR2	1.0	55	160	294	.86	3.43	25.1%
CONT3	0.5	60	130	358	.25	1.94	-
CISR2	0.5	75	210	504	.53	3.05	40.78%

*…… Refers to load at initiation of first flexural crack.
**…. Refers to load at initiation of first shear crack.
†…… Average of two specimens

3.1 Test Results of Unstrengthened Corbels (Control Corbels)

During loading of Specimen CONT1, the first major crack appeared at 50 kN as depicted the first crack was a vertical crack appearing approximately at the corbel face close to the column side. The other crack was a diagonal crack almost at an angel of 45 degrees (i.e. shear crack), this was at a load level 41% of the ultimate failure load (i.e. there was a high level of ductility) diagonal shear cracks formed at a load level of 120 kN. As the load increased, this crack started to widen and propagated leading to failure at a load level of 292 kN. Increasing the load led to new diagonal cracks and the diagonal cracks propagated rapidly until failure.

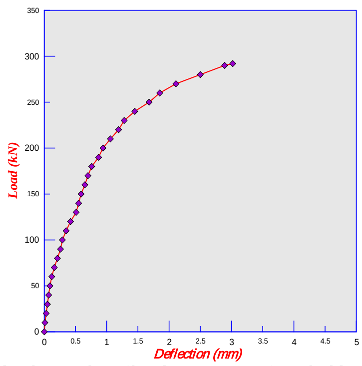


Fig. (3.1) Load-Deflection Curve of corbel(CONT1)

3.2 Strengthening Effect of Using CFRP Strips

To study the effect of strengthening reinforced concrete corbels with ***horizontal*** externally bonded carbon fibre reinforced polymer strips, series corbel specimens CHS were strengthened with two (CHS2), three (CHS3) and four (CHS4) layers of CFRP strips and with layer width 36mm for corbel specimen CHS2, 18.0mm for both corbel specimens CHS3 and CHS4.

For specimens CHS2, The first crack to appear during the loading sequence was a flexural crack similar to that of a cantilevered beam. While a second crack started at the bearing plate, and propagated towards the junction of the column and face of the corbel. This crack caused failure of the corbel. The corbel failed at an ultimate load of (335 kN) with an increase in strength of about (14.7 %) compared to unstrengthened corbel specimen CONT1 (control corbel).

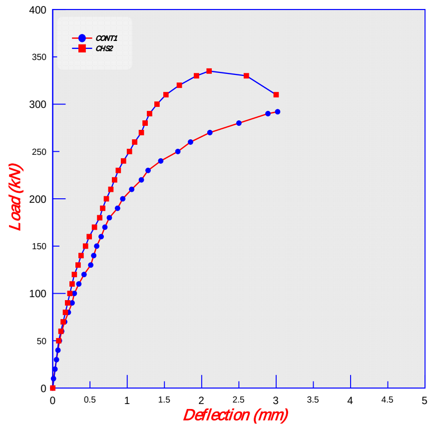


Fig. (3.2) Load-Deflection Curve of corbel (CHS2)

Specimen CHS3 shared similar failure patterns. Flexural cracks were observed first, at approximately a load level 60kN and then a few diagonal cracks were observed. With increasing load the flexural cracks grew upward and became wider. The first major crack appeared at a load level of 150 kN and ultimate load increased to 370 kN. The ultimate load was larger than those of CHS2 and CHS4. At this stage there was no deterioration in the concrete itself as those occurred in the other specimens.

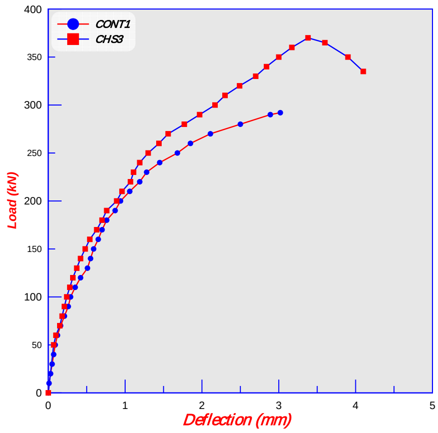


Fig. (3.3) Load-Deflection Curve of corbel (CHS3)

Specimen CHS4 was strengthened with four horizontal layers of CFRP strips having 18.0mm width. During loading, diagonal shear cracks formed at a load level of 130 kN. The first shear crack was the critical crack in this corbel. Fig.3.4 shows the load versus deflection curves of corbel specimens CONT1 and CHS4.

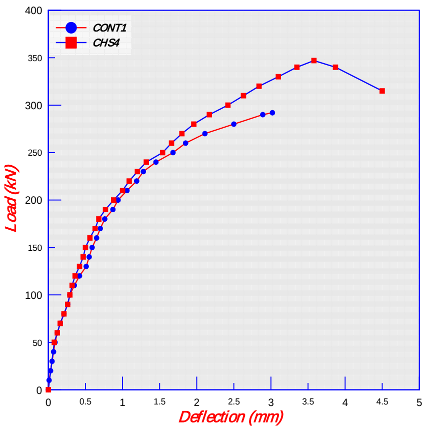


Fig.(3.4) Load-Deflection Curve of corbel (CHS4)

For this corbel specimens series CHS, a shear failure of the concrete occurred where multiple cracks formed, which were combinations flexural and diagonal-splitting types of cracks.

Specimens of Series CHSR consisted of four corbel specimens designated as CHSR2, CHSR3, CHSR4 and CHSR1. The failure and crack patterns of series CHSR2-CHSR4 corbels were somewhat similar to those occurred in series CHS in spite of the variation in the ductility, where series specimens CHSR was more ductile" no

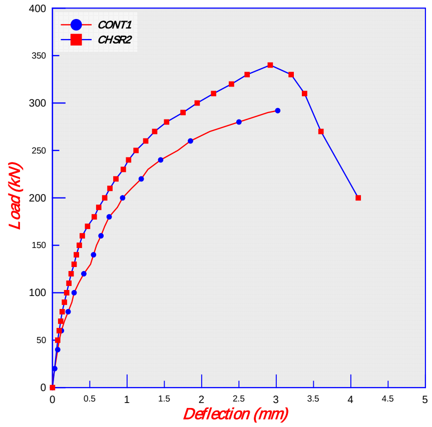


Fig.(3.5) Load-Deflection Curve of corbel (CHSR2)

change in ultimate load but the deflection increases with a decrease in load due to the confinement caused by the CFRP strips" . The ultimate loads were 340, 383 and 353kN for CHSR2,CHSR3 and CHSR4 respectively. Figs 3.5, 3.6, 3.7, and 3.8 shows load versus deflection curves for these corbel specimens.

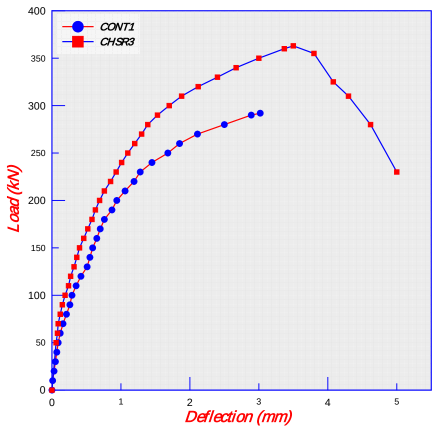


Fig. (3.6)Load-Deflection Curve of corbel (CHSR3)

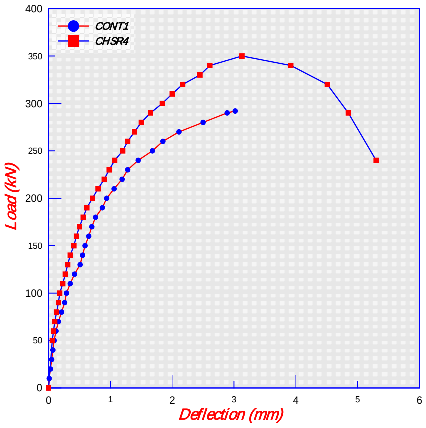


Fig. (3.7) Load-Deflection Curve of corbel (CHSR4)

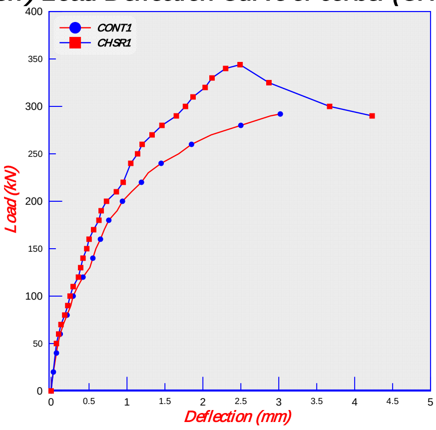


Fig.(3.8)Load-Deflection Curves of corbel (CHSR1)

To study the effect of strengthening reinforced concrete corbels with ***inclined*** externally bonded carbon fibre reinforced polymer strips, three corbel specimens CIS2, CIS3 and CIS4 were strengthened with two, three and four layers of CFRP strips having 3.6,18.0 and 18.0mm width respectively. The major differences between series CHS, and CIS were the area of secondary cracks and the spalling of the concrete between the cracks.

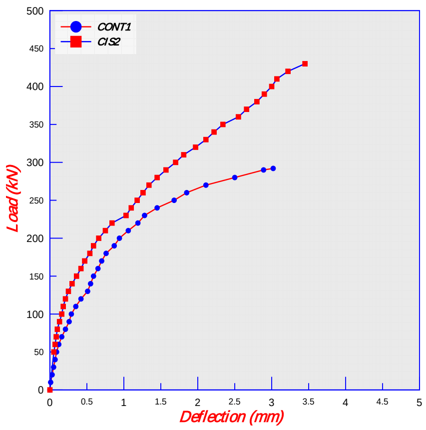


Fig.(3.9) Load-deflection Curve of corbel (CIS2)

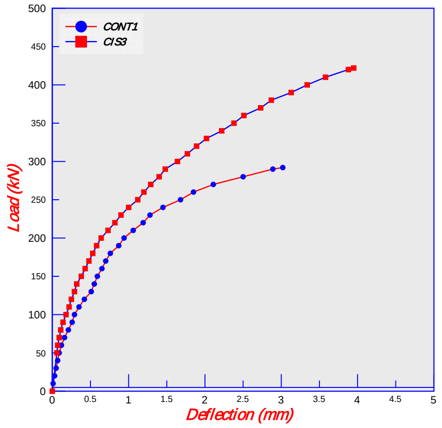


Fig.(3.10)Load-Dflection Curve of corbel (CIS3)

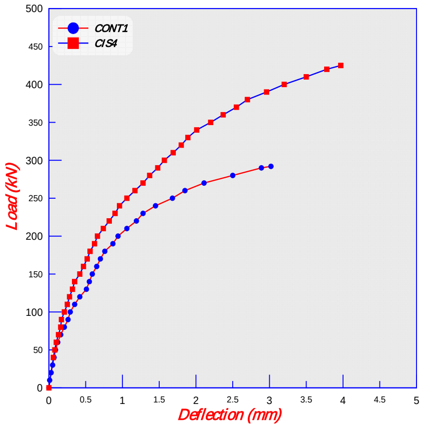


Fig.(3.11) Load-Deflection Curve of corbel (CIS4)

Corbel Specimens of Series CISR consisted of three corbel specimens CISR2, CISR3, and CISR4. These corbel specimens were strengthened in similar manner of corbel specimens in series CIS except that the CFRP strip was not terminated at the face of corbel but extended as U or∩ shape. Fig. 3.12, 3.13 and 3.14 show the load-deflection curves throughout the entire stages of loading for the corbel specimens CISR2, CISR3 AND CISR4.

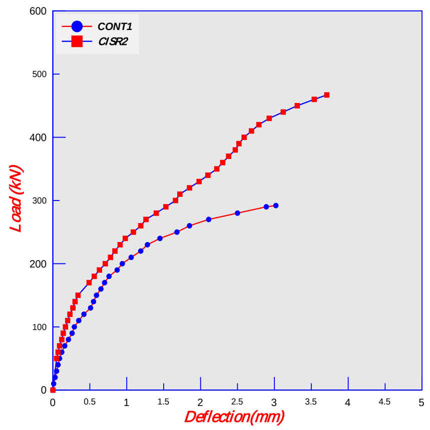


Fig.(3.12)Load-Deflection Curve of corbel (CISR2)

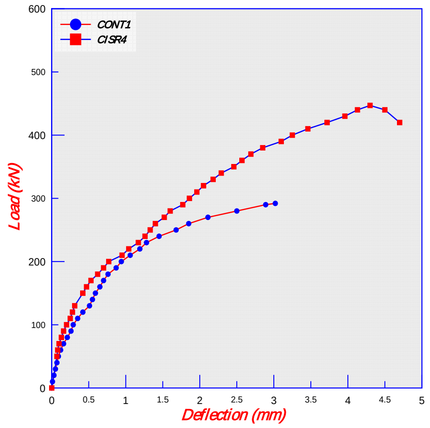


Fig.(3.13) Load-Deflection Curve of corbel (CISR4)

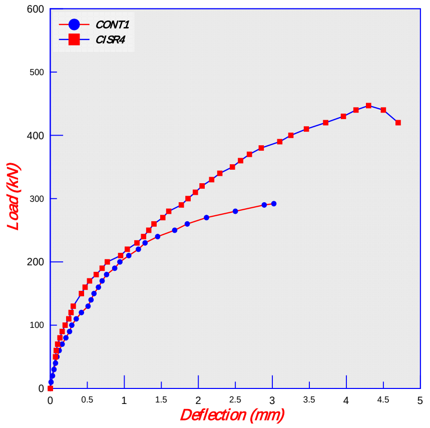
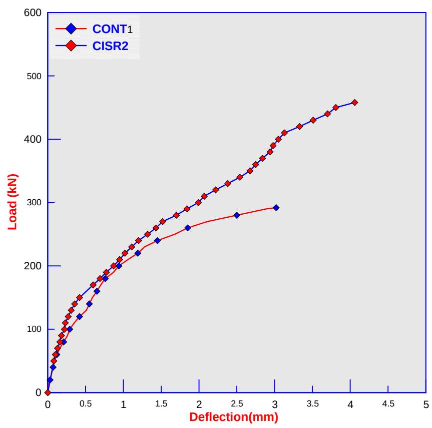


Fig.(3.14) Load-Deflection Curve of corbel(CISR4)

3.3 Repaired Specimen (CISR2)

It is decided to load the repaired corbel specimen approximately to a load level of 175 kN (60% of ultimate load) according to control corbel CONT1, then strengthened by CISR2 system because it is the best system of strengthening. Test results of specimen results in a similar behaviour of specimen CISR2, but with a less stiffness than specimen due to pre-cracking. The load-deflection curve are shown in Fig 3.15.



Fig(3.15)Load-Deflection Curve of corbel (CISR2 repair)

Fig. 3.16 shows a comparison of the by load-deflection curves for the best strengthened corbel specimens from all series, CHS, CHSR,CIS, and CISR.

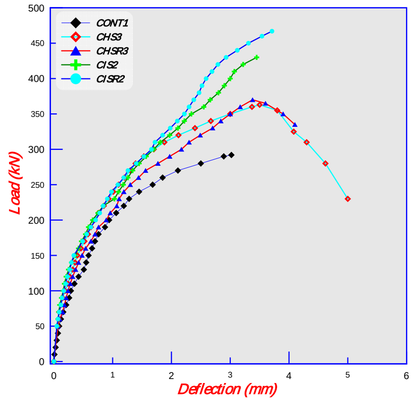


Fig. (3.16) Load-deflection curves of corbels CONT1,CHS3,CHSR3,CIS2.CISR2

3.4 Effect of Shear Span to Effective Depth (a/d) Ratio

The effect of shear span to depth ratio (a/d) was investigated in this research work. Corbels with two different (a/d) ratios (1.0 and 0.5) were used in addition to (a/d=0.7). These values were used for unstrengthened specimens, and with the best result of all series of strengthened corbel specimens for (a/d=0.7). Table 3.1 shows the predicted ultimate shear strength obtained using these ratios.

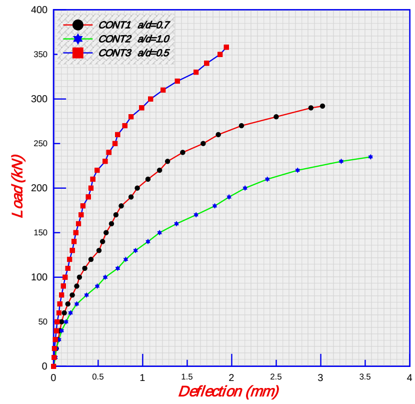


Fig.(3.17)Load-Deflection Curves for Unstrengthened Corbels CONT1, CONT2, and CONT3 (a/d= 0.7, 1.0 and 0.5)

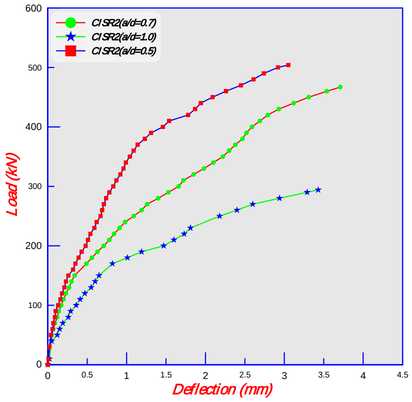


Fig.(3.18) Load-Deflection Curves of corbel CISR2 (a/d= 0.7, 1.0 and 0.5)

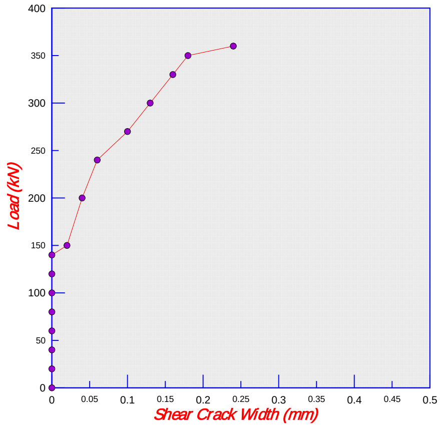


Fig.(3.20) Load-Shear Crack Width of corbel (CHS3)

3.5 Shear Crack Width

For all corbels, the first cracks were flexural cracks starting at or near the junction of the tension face of the corbel and the face of the column. Shear cracking load is defined as the load at which the first major inclined diagonal tension crack appears in the shear span. Corbels without CFRP strips exhibited considerably larger crack width at failure. The data of crack width was recorded up to 90% or 95% of the ultimate load, where the final width of crack at ultimate load cannot be measured due to explosive rupture of the CFRP strips.

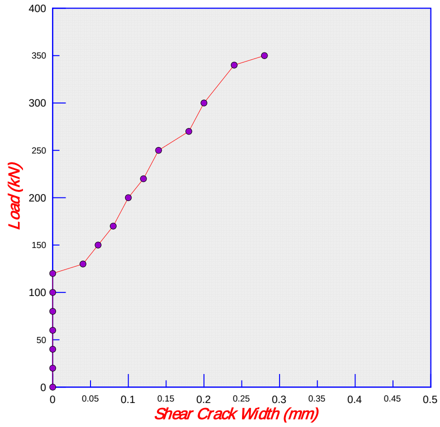


Fig.(3.21) Load-Shear Crack Width of corbel (CHSR3)

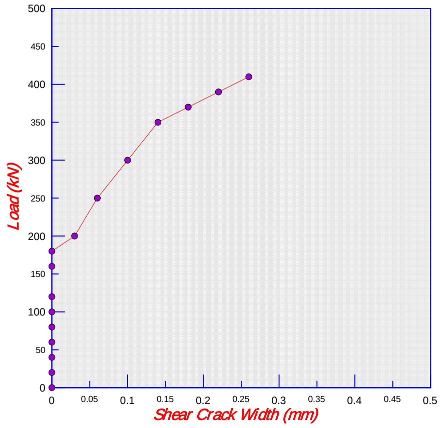


Fig.(3.22) Load-Shear Crack Width of corbel (CIS3)

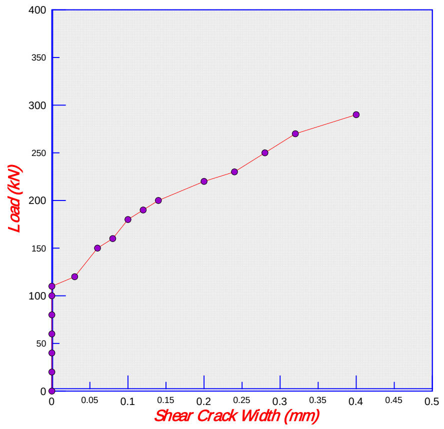


Fig.(3.19) Load-Shear Crack Width of corbel (CONT1)

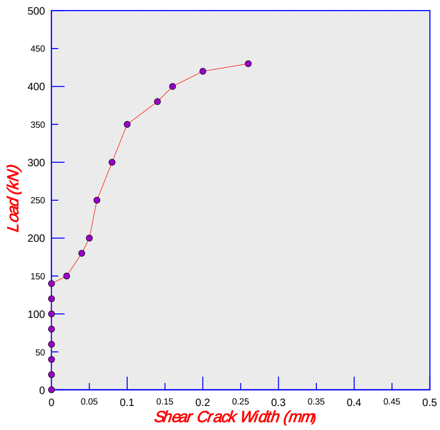


Fig.(3.23) Load-Shear Crack Width of corbel (CISR3)

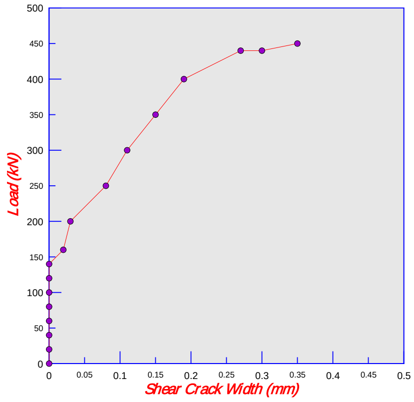


Fig.(3.24)Load-Shear Crack Width of repaired corbel (CISR2 repair)

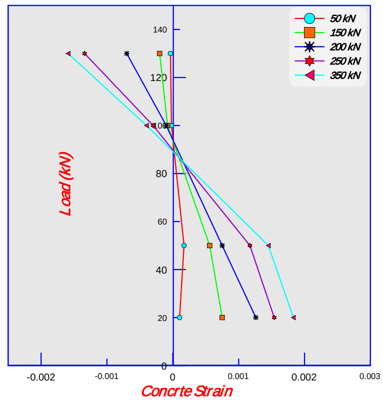


Fig.(3.26)Concrete strain distribution of Corbel (CHS3)

3.5 Concrete Surface Strains

Concrete surface strains at a section close to column face of the tested corbels were measured by using six to ten demec discs over the depth of the corbel. Figs.3.25 to 3.28 show the concrete strain distribution over the corbel depth for all corbels at different load levels. In these figures, it can be seen that the strain distribution was approximately linear in tensile and compressive zones at low load levels, and then became increasingly nonlinear at the tension zone at higher loads due to cracking effect. For all tested corbels, the neutral axis was shifting upwards after increasing the load beyond than the load at first crack. The strains in the tension zone were measured by including widths of cracks within gauge length (not true strains) .

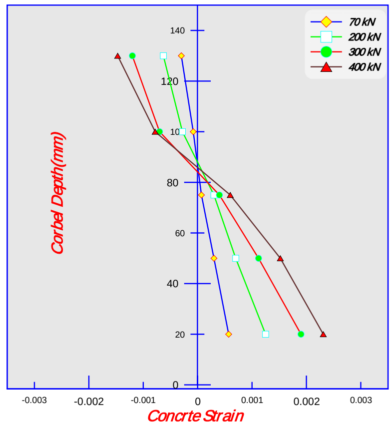


Fig.(3.27)Concrete strain distribution of Corbel (CIS3)

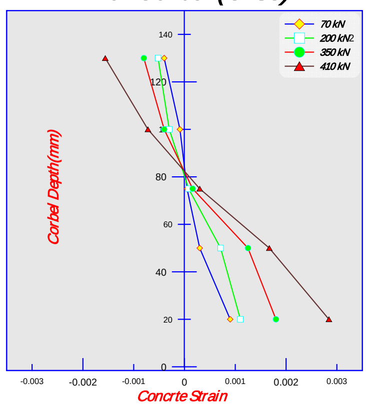


Fig.(3.28)Concrete strain distribution of Corbel (CISR3)

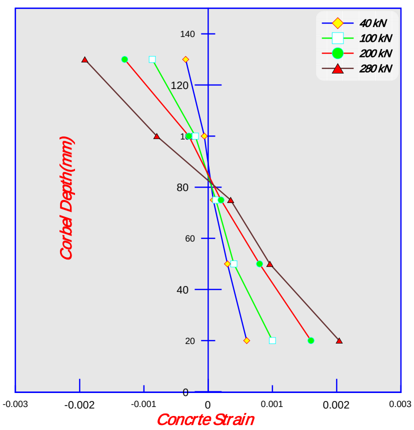


Fig.(3.25)Concrete strain distribution of Corbel (CONT1)

3.6 Tensile Strain in CFRP Strips

The load- FRP strains (in the direction of the fibre strips orientation) measured at the center of the strips by demec points which were placed at different positions along horizontal or inclined CFRP strips. The strain values indicated in the figs. of this section are those obtained at regions with maximum strain values as shown in Figs 3.29 to 3.38. From testing, it can be observed that the maximum strain values along each strip occur at regions that intersect with the diagonal shear crack. From the curves shown in these Figures, it can be observed that the strains in the CFRP strips were very small before the initiation of the diagonal shear cracks and began to increase rapidly after the formation of the shear cracks, and it can be noticed that the maximum strains occurred at the strip which lies at the middle of the shear span. Table 3.2 shows the maximum strains for all tested corbels.

Table 3.2 Maximum strains developed in CFRP strips for all tested corbels.

Corbel designation	Type of strip	Strip1	Strip2	Strip3	Strip4
CHS2	Horizontal	0.004	0.003	---	---
CHS3	Horizontal	0.0036	0.0044	0.002	---
CHS4	Horizontal	0.0033	0.0046	0.004	0.0032
CIS2	Inclined	0.0045	0.0051	---	---
CIS3	Inclined	0.0011	0.0027	0.004	---
CIS4	Inclined	0.0012	0.0036	0.0042	0.0037
CISR2	Inclined	0.0054	0.0049	---	---
CISR3	Inclined	0.00015	0.0042	0.0046	---
CISR4	Inclined	0.00062	0.0053	0.005	0.004
CISR2 repair	Inclined			---	---
CISFR4	Inclined	0.00103	0.0018	0.004	0.0036

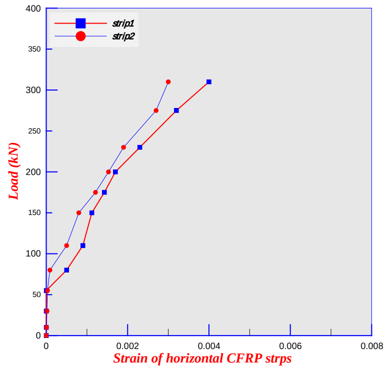


Fig (3.29) Development of tensile strain in horizontal CFRP strips of corbel CHS2.

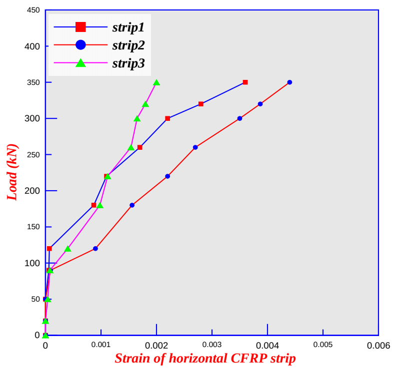


Fig (3.30) Development of tensile strain in horizontal CFRP strips of corbel CHS3.

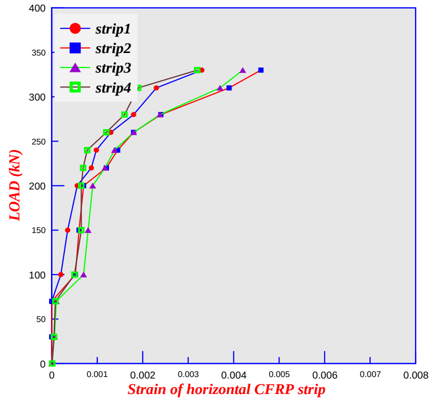


Fig (3.31) Development of tensile strain in horizontal CFRP strips of corbel CHS4.

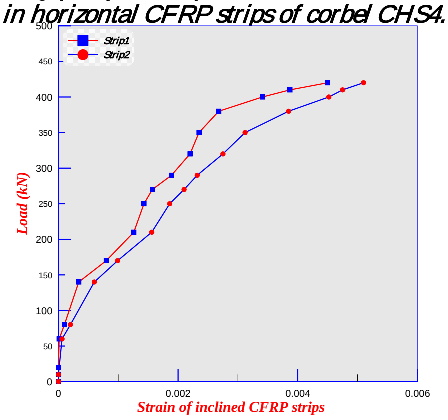


Fig (3.32) Development of tensile strain in inclined CFRP strips of corbel CIS2.

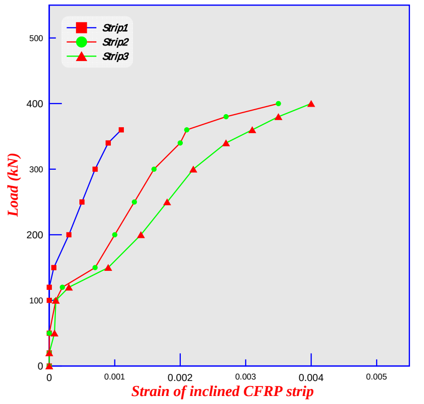


Fig (3.33) Development of tensile strain in inclined CFRP strips of corbel CIS3.

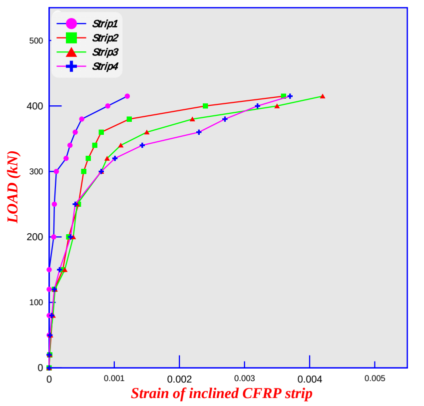


Fig (3.34) Development of tensile strain in inclined CFRP strips of corbel CIS4.

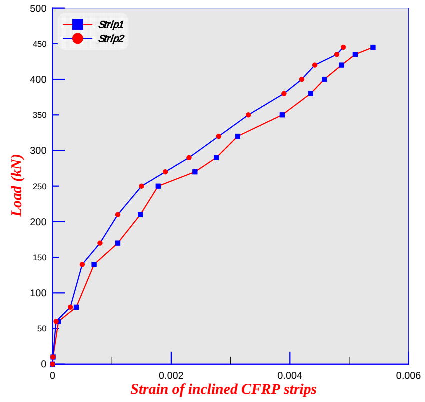


Fig (3.35) Development of tensile strain in inclined CFRP strips of corbel CISR2.

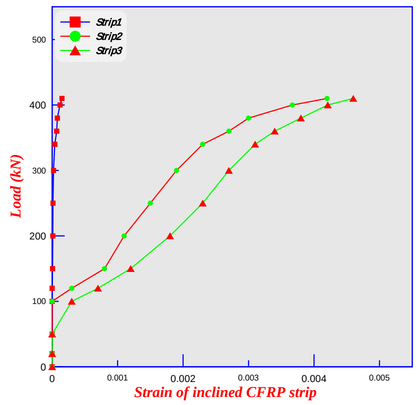


Fig (3.36) Development of tensile strain in inclined CFRP strips of corbel CISR3.

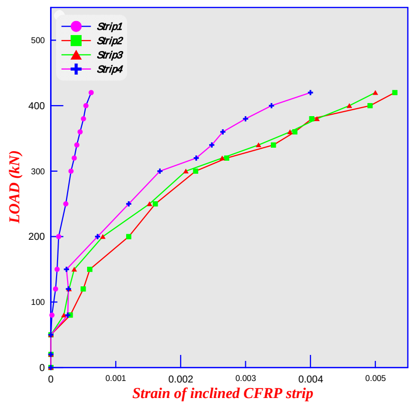


Fig (3.37) Development of tensile strain in inclined CFRP strips of corbel CISR4.

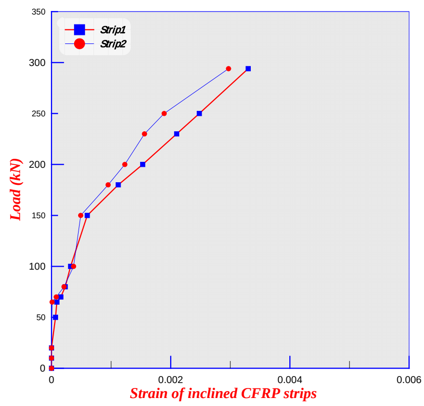


Fig (3.38) Development of tensile strain in inclined CFRP strips of corbel CISR2(a/d=1.0).

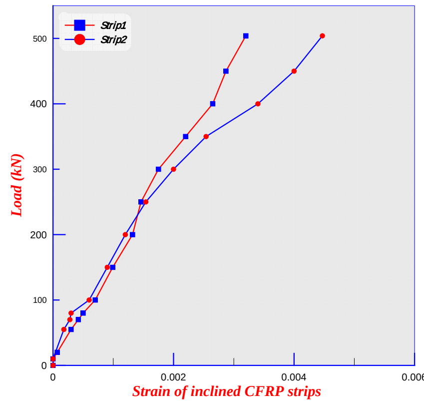


Fig (3.39) Development of tensile strain in inclined CFRP strips of corbel CISR2(a/d=0.5).

4- Conclusions

Based on the overall results obtained from the experimental work for the externally strengthened or repaired reinforced concrete corbels by CFRP strips, the following conclusions can be drawn:

● Using CFRP strips for strengthening can increase the ultimate shear strength of RC corbels and enhances the flexural stiffness, where the percentage of increase is about (44.5 - 60) % for inclined strips and (14.726 - 31.164)% for horizontal strips compared to control corbel.

● The distribution, location, orientation and amount of CFRP strips play an important role in upgrading the strengthened members; therefore, strengthening the specimens by inclined CFRP strips gives the best results if compared with the other strengthened models (horizontal strengthening technique). This may be due to the orientation of the CFRP strips being perpendicular to the inclined cracks.

● Using CFRP sheets as external strengthening has a significant effect on first cracking loads where the percentage increase in cracking load for horizontal technique was 18.75% while the percentage increase in cracking load for inclined technique was 51.43%.

● In horizontal strengthening technique, specimens strengthened with CFRP strips and full warped around the corbel, have small effect on ultimate load compared to specimens which strengthened on two side . While the full warped strengthening increase the ductility of the specimens, which may be attributed to the confinement that is provided by the CFRP.

- CFRP in most cases of strengthened corbels neither ruptured nor debonded, but a peel of concrete with splitting CFRP strips was 0bserved. It means that all strengthened model used in the present study are successful in upgrading such situation.
- For the corbel repaired with CFRP strips in shear, the ultimate load increased by (56.68%) with respect to ultimate load of the control corbel.
- The average decrease in the width of cracks due to the presence of CFRP strips was about 24.285 % and 40.834% of the crack width of the control corbels at ultimate load levels for horizontal and inclined technique respectively.

5-References

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