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Experimental Behavior of Self Compacting Concrete Corbels Strengthened with External CFRP

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Abstract- *This research aims to study the influence of using Carbon Fiber Reinforced Polymer (CFRP) strips as an external strengthened and repairing material on the behavior of self-compacting concrete (SCC) Corbels. The experimental work involved testing twenty self-compacting concrete corbels specimens. The experimental work is divided into two parts; the first part consists of three groups to investigate the most effective direction, position, bonding type and amount of CFRP strips on the behavior of corbels and utilized it in practice, also to strengthen new variables that are investigated in the second part. Two groups in part one are strengthened with different numbers of inclined and horizontal direction of CFRP strips, while in the third group the specimens were strengthened with strips of CFRP having different directions and bond types to improve the strength capacity and behavior of corbels. This improvement is represented by increase cracking load by about (94)% and increase in their ultimate load capacity of strengthening corbels which varies from about (19 to 88)%. While the second part of experimental work included the following variables: shear span to effective depth ratio (a/d), amount of horizontal steel reinforcement stirrups and repaired damaged corbels. The reinforced concrete corbels in this part were strengthened and repaired by CFRP strips depending on optimum result that is produced from part one wherefrom position, direction and amount are considered. It was found for un-strengthened and strengthened corbels having same horizontal secondary reinforcement stirrups that when (a/d) ratio decreases from 0.65 to 0.4 causes increase in cracking and ultimate loads reach (55)% and (35.41)% respectively. For un-strengthened and strengthened corbels having same (a/d) ratio, it was found an increase in cracking load which varies from (6.66 to 34.78)% and from (18.18 to 52.63) % in ultimate load when horizontal secondary reinforcement stirrups are increased. It was also found repairing SCC corbels with CFRP strips causes an increase in ultimate load reaching up to (50)% with respect to un-strengthened specimens. From results it is concluded that strengthened or repaired corbels present stiffer load deflection response than corresponding un-strengthened corbel (control corbel).*

Keywords- *Corbel, Strengthen, SCC, Carbon Fiber.*

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1. Introduction

Corbels (or brackets) are short-hunched cantilevers having shear span-depth ratios less than unity. They are usually built monolithically with columns or walls and project from the inner face of them to support heavy concentrated load of pre-cast beams, gantry girders and other pre-cast system loads. The design of corbels is continuously changing in recent years, due to the complexity of detailing and crowded of reinforcement, also this crowded could lead to difficulties in achieving fully compacted concrete, and result in a poorer bond between reinforcement and concrete . One solution to this problem is to use self-compacting concrete (SCC) [1]. In the last years, there have been main efforts to develop or find a composite building material that supply sufficient amount of resistance, ductility, and durability. With ease of maintaining and acceptable cost, thus hundreds of researches and papers published to reach this goal. One of the composite materials in civil engineering and used in this research is carbon fiber reinforced Polymer (CFRP) with adjusting resin. The survey of the previous literature shows that, there are many studies on the behavior of corbels with different criteria, including the corbels dimension and reinforcement and using steel fibers [2] strength of concrete [3] using SCC instead of the vibrated one [1]. In addition, the behavior of reinforced concrete corbel strengthened by CFRP was studied [4, 5] but no experimental study was found that deals with SCC corbels strengthening or repaired using CFRP strips. Therefore, the present study concentrates on the effect of CFRP strips when used to strengthen SCC corbels.

2. Experimental Program

The experimental program is divided into two parts; the first part consists of three groups to investigate the most effective direction, position, bonding type and amount of CFRP strips on the behavior of SCC corbels by keeping shear span to effective depth ratio (a/d) and amount of horizontal steel reinforcement stirrups constant. While the second part of experimental work included the following variables: (a/d), and repaired damage corbels by CFRP strips. The reinforced concrete corbels in this part strengthened and repaired by CFRP strips depended on optimum result found from part one wherefrom direction, position, bonding type and amount of CFRP strips.

I. Corbel Details

The test specimen consisted of double corbels and a short column. The dimensions of the test specimen are shown in Figure 1. For all corbels, the overall dimensions, column size and the main reinforcement were kept constant throughout the investigation. The column dimensions were 200mm by 150mm in cross section and 600mm long. Corbels had a cantilever projection from either side of column with length of 250mm, 150mm thickness. Column with four deformed steel bars having a 12mm diameter was reinforced and supported by ties having a 6 mm diameter placed at a pitch of 130mm center to center. Three primary reinforcement (main bars) having diameter 12mm of deformed steel bars placed at the tension side with cover 25mm. Closed to end of each corbels, main bars were welded with cross bar of 12mm diameter to provide addition anchorage [6]. Three different amounts of secondary horizontal closed stirrups were used in this research work (2Ø6mm, 1Ø6mm and without deformed bars) distributed over the upper two thirds of the effective depth at the column face [6].

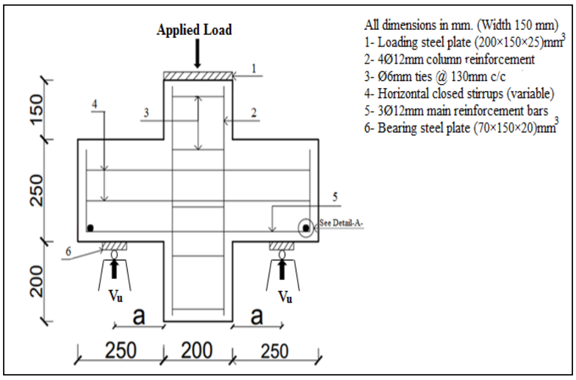


Figure 1: Dimensions and Reinforcement Details of the Tested Specimens

II. Materials

1) Cement

Ordinary Portland cement (Type I) with trade name (Mass), manufactured by (Tasluja-Bazian) factory (Iraq), is used throughout this work. It satisfies the requirements of the Iraqi Standard Specification No.5, 1984 [7].

2) Aggregate

The Natural fine aggregate (sand) brought from Al-Ukhaidur region while the coarse aggregate was crushed gravel with a maximum size of 14mm from Al-Niba'ee region. Both fine and coarse aggregate satisfies the requirements of the Iraqi Standard Specification No.5, 1984 [8].

3) Limestone Powder (LSP)

This material is locally named as "Al-Gubra". It is a white grinded material from limestone. The limestone powder, sieved through a 1.18 mm sieve.

4) Superplasticizer

Third generation superplasticizer, known commercially as "GLENIUM 54", according to ASTM C494-05a [9] used throughout this work.

5) Water

Tap water is used for both mixing and curing of concrete.

6) CFRP Strips and Bonding Material

CFRP of type SikaWrap®-300 C/60 with roll width of 300mm. The bonding material is epoxy based impregnating resin of type Sikadur®-330 that consists of two compounds, compound A (white color) and compound B (gray color) were used throughout this study. The properties of CFRP and epoxy (Supplied by the manufacturer) are shown in Tables 1 and 2.

3. SCC Mix

Table 3 shows the SCC mix that designed according to EFNARC [10] to satisfy SCC fresh properties and have a compressive of cylinder strength ranging between (30 to 34)MPa at 28 days age.

Table 1: Properties of CFRP

Tensile strength (MPa)	Thickness (mm)	Weight (g/m^2)	Elongation at break (%)	Tensile modulus (MPa)	Density (g/cm^3)
3900	0.166	300	1.5	230000	1.79

Table 2: Properties of the Epoxy

Tensile strength (MPa)	Elongation at break (%)	Flexural modulus (MPa)	Mixing Ratio by Weight	Setting Time (minute)	Density Mixed (g/cm^3)
30	0.9	3800	4:1	30	1.31

Table 3: SCC mix proportions

Cement kg/m^3	Aggregate		LSP kg/m^3	Super-plasticizer Liter/m^3	Water Liter/m^3
	Fine kg/m^3	Coarse kg/m^3			
350	797	767	170	4.9	190

4. CFRP System Installation

Prior to bonding CFRP to the corbel, the surface of concrete at all faces of the corbel sides was grinding to remove any weak, loose materials by and rounded all corners of the corbel as ACI 440.2R-08 [11] suggested. The location of CFRP strips was washed with water and dried, then clean the surface well by thinner to remove the dust and oils on the concrete surface. After that, two-parts of Sikadure-330 (Compound A and Compound B) in 4:1 proportion were mixed by using an electrical mixer until it becomes homogeneous with gray color. The epoxy mixer applied on the surface of concrete at position of CFRP strips to fill any possible cavities. Applying the CFRP strips to its designated place and use a rubber roller with direction of the fiber to remove air bubbles and to avoid any distortion to the fiber orientation. Then coat the CFRP with a thin layer of epoxy and left the corbels inside the laboratory to allow the epoxy for setting.

5. Strengthening Corbels by CFRP Strips

Strengthened schemes were chosen carefully based on the field conditions and the practical needs, mainly, economic and crack pattern. In this research work, all the twenty corbel specimens describe with details in Table 4.

6. Experimental Results

The main aim of this research is to investigate the effect of carbon fiber polymer strips (CFRP) when used as strengthening and repairing SCC corbels; this includes its influence on the ultimate strength and behaviors of the corbels. During loading for all corbel, the first crack appeared at the junction of tension in the corbel and the face of column in vertical direction (future crack), then a new inclined shear crack propagated slowly accompanied by form a new shear cracks parallel to initial inclined crack and propagated rapidly until failure. For each tested corbel, load versus deflection at the center of the tested corbels using a dial gage of 0.01mm accuracy, first cracking loads, ultimate loads, cracking patterns and modes of failure are recorded for each tested corbel specimen as shown in Table 5.

I. Effect direction, position, amount and type of bonding CFRP strips

Table 5 and Figures 2-4 show load-deflection curve of three groups of corbel specimens that used to study the effective direction ,position, amount and bonding type (face and wrap) of CFRP strengthening corbels with constant (a/d=0.65) and horizontal secondary reinforcement stirrups (2Ø6). The results for group (1) in Figure 2 indicate that applying three horizontal CFRP strips distributed on 2d/3 from the bottom edge of the main tension reinforcement give the best strengthening, while applying fourth horizontal one (in the upper edge) did not give an extra significant strengthening, due to its existence in the compression zone. Figure 3 shows the results of group 2, and indicate that the installation of incline strips perpendicular to shear crack pattern give effective strengthening configuration. There were a delay in first and failure cracks formation in addition to increase in ultimate load with the increasing of CFRP inclined strips compare to CONT1, as shown in Table 5. Figure 4 shows the results of group 3, which indicate that the presence of CFRP as a box and U or ∩ shape gives better improvement in strength from previous groups, especially specimen C_1I_3W which cause increase in ultimate strength of the control corbel CONT1 by 62.5% while reduce the deflection at same load level, this indicate increase in stiffness and ductility of the corbels with increasing the CFRP strips that using to strengthen it, as shown in Table 5.

II. Effect of Shear Span to Effective Depth Ratio (a/d) of SCC Corbels

Figures 5 and 6 show the effect of shear span to depth ratio (a/d) on the behavior of un-strengthened ad strengthened SCC corbels, with constant horizontal secondary reinforcement stirrups (2Ø6mm). Results indicate that using lower (a/d) ratio (0.4) cause higher ultimate strength by 28.9% and 35.4% for CFRP strengthened and un-strengthened samples respectively compared to those with (a/d) ratio of 0.65, as shown in Table 5.

III. Effects of Horizontal Secondary Reinforcement Stirrups for SCC Corbels

Figures 7 and 8 show the effect of the amount of horizontal secondary reinforcement stirrups (2Ø6mm, 1Ø6mm and without deformed bars) on SCC corbels, with constant a/d=0.4. The results indicate that the increase of horizontal secondary reinforcement stirrups from zero to 2Ø6mm cause increase the un-strengthened (by CFRP) corbels cracking and ultimate loads by about 23% and 48% respectively. These percentages become by about 35% and 53% respectively for corbels strengthened with CFRP strips, as shown in Table 5.

IV. Effect of Repairing Corbel Specimens by External CFRP Strips

Two specimens have been used $C_2I_3H_3WR$ and $C_4I_3H_3WR$ with horizontal secondary reinforcement stirrups (2Ø6mm) and without it respectively, with keeping (a/d=0.4) constant to investigate repairing with optimum scheme combine strengthening by CFRP strips. The corbel specimens ($C_2I_3H_3WR$ and $C_4I_3H_3WR$) subjected to a damage ratio equal to 40% of ultimate load according to control corbels CONT2 and CONT4 respectively, before trying to repair them by CFRP strips. The damage ratio is the ratio between the load applied to the specimen before the repair and the ultimate load capacity of the un-strengthened control specimen. Figures 9 and 10 show that the strengthening the damaged corbels with CFRP strips not only regain their original strength, but increase their ultimate load by (39-51)% depending on the presence of horizontal secondary reinforcement stirrups in it, as shown in Table 5.

Table 4: Details of CFRP Strengthened for Test Specimens

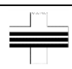
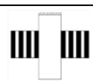
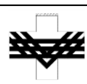
Symbol	CFRP Strengthened Details	Strengthening Schemes
CONT1, CONT2, CONT3, CONT4	Control specimen without strengthening	
C_1H_1F	Specimen strengthened with one horizontal strip at two sides only	
C_1H_2F	Specimen strengthened with two horizontal strip at two sides only	
C_1H_3F	Specimen strengthened with three horizontal strip at two sides only	
C_1H_4F	Specimen strengthened with four horizontal strip at two sides only	
C_1I_1F	Specimen strengthened with one incline strip mirrored on each side in 45º at two faces only	
C_1I_2F	Specimen strengthened with two incline strip mirrored on each side in 45º at two faces only	
C_1I_3F	Specimen strengthened with three incline strip mirrored on each side in 45º at two faces only	
C_1H_3W	Specimen strengthened with three horizontal strips as a box shape at all faces.	
C_1I_3W	Specimen strengthened with three incline strips as U or ∩ shape mirrored on each side at three faces.	
C_1V_4W	Specimen strengthened with four vertical strips as a box shape at all faces.	
$C_1I_3H_3W$	Specimen combine strengthening with three incline strips as U or ∩ shape mirrored on each side at three faces and three horizontal strips as a box shape at all sides thus $C_2I_3H_3W$, $C_3I_3H_3W$ and $C_4I_3H_3W$.	
$C_2I_3H_3WR$	Specimen combine repairing with three incline strips as U or ∩ shape mirrored on each side at three faces and three horizontal strips as a box shape at all faces thus $C_4I_3H_3WR$.	

Table 5: Test Results of All the Specimens

Specimen	Secondary Rein. Stirrups	a/d Ratio	First crack Stage		Ultimate Stage		Increase in ultimate load with respect to control corbel %
			$V_{cr(f)*}$ (kN)	$V_{cr(s)**}$ (kN)	V_u (kN)	Δ_u (mm)	
CONT1	2Ø6mm	0.65	60	95	240	4.3	__
C_1H_1F	2Ø6mm	0.65	65	110	285	3.95	18.75
C_1H_2F	2Ø6mm	0.65	70	125	300	3.75	25
C_1H_3F	2Ø6mm	0.65	75	150	325	3.54	35.41
C_1H_4F	2Ø6mm	0.65	75	160	330	3.39	37.5
C_1I_1F	2Ø6mm	0.65	75	130	305	3.8	27.08
C_1I_2F	2Ø6mm	0.65	80	145	340	3.98	41.66
C_1I_3F	2Ø6mm	0.65	80	165	365	4.03	52.08
C_1H_3W	2Ø6mm	0.65	85	180	355	3.52	47.91
C_1I_3W	2Ø6mm	0.65	90	190	390	3.84	62.5
C_1V_4W	2Ø6mm	0.65	75	160	325	3.98	35.41
$C_1I_3H_3W$	2Ø6mm	0.65	100	230	450	4.53	87.5
CONT2	2Ø6mm	0.4	80	150	325	4.05	__
$C_2I_3H_3W$	2Ø6mm	0.4	155	315	580	5.05	78.46
$C_2I_3H_3WR$	2Ø6mm	0.4	__	260	490	4.98	50.76
CONT3	1Ø6mm	0.4	75	125	260	3.8	__
$C_3I_3H_3W$	1Ø6mm	0.4	140	295	450	4.4	73.07
CONT4	__	0.4	65	110	220	3.9	__
$C_4I_3H_3W$	__	0.4	115	280	380	4.55	72.72
$C_4I_3H_3WR$	__	0.4	75	190	305	4.3	38.63

*… Load at first flexural crack
** …Load at first shear crack

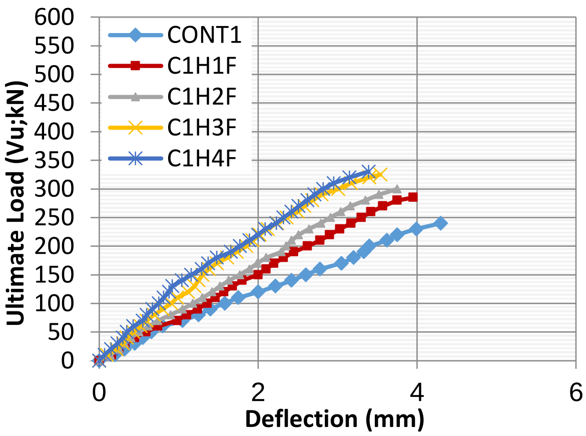


Figure 2: Load-Deflection Curve of Specimens in Group 1 (C_1H_1F, C_1H_2F, C_1H_3F, and C_1H_4F)

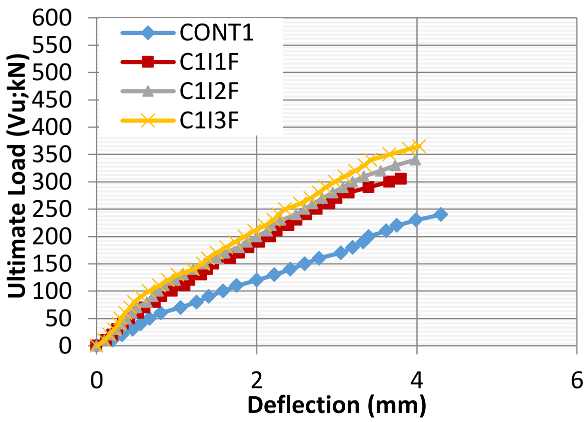


Figure 3: Load-Deflection Curve of Specimens in Group 2 (C_1I_1F, C_1I_2F and C_1I_3F)

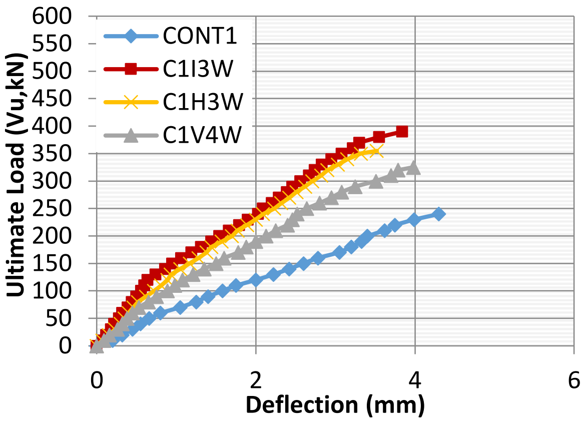


Figure 4: Load-Deflection Curve of Specimens in Group 3 (C1H3W, C1I3W and C1V4W)

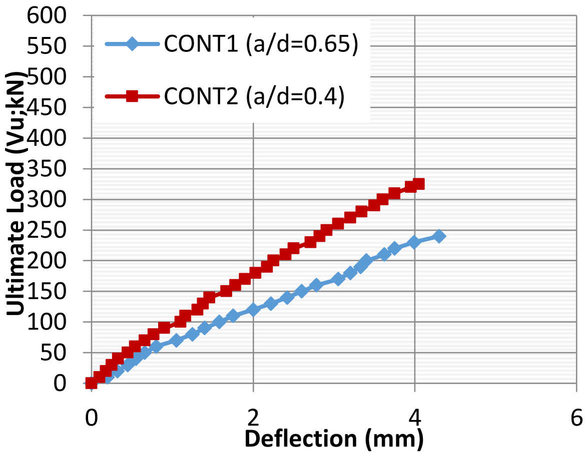


Figure 5: Load-Deflection Curves for Un-Strengthened Corbels CONT1 and CONT2 with Different Values of (a/d)

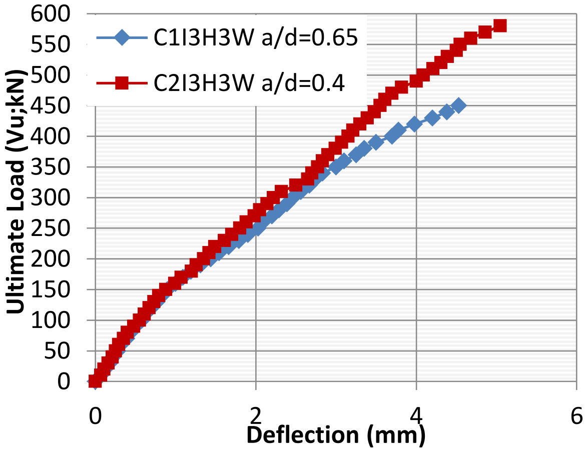


Figure 6: Load-Deflection Curves for Strengthened Corbels $C_1I_3H_3W$ and $C_2I_3H_3W$ with Different (a/d) Ratio

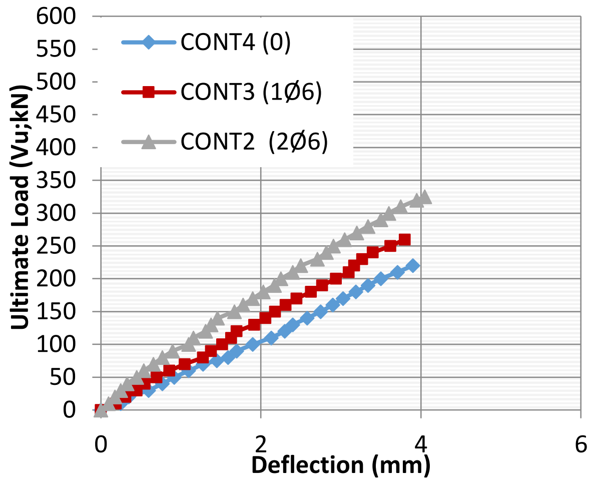


Figure 7: Load-Deflection Curves for Un-Strengthened Corbels with Different Values of Horizontal Secondary Reinforcement

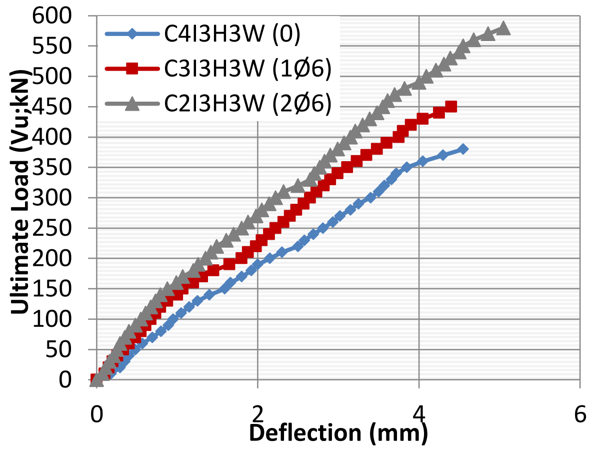


Figure 8: Load-Deflection Curves for Strengthened Corbels with Different amount of Horizontal Secondary Reinforcement

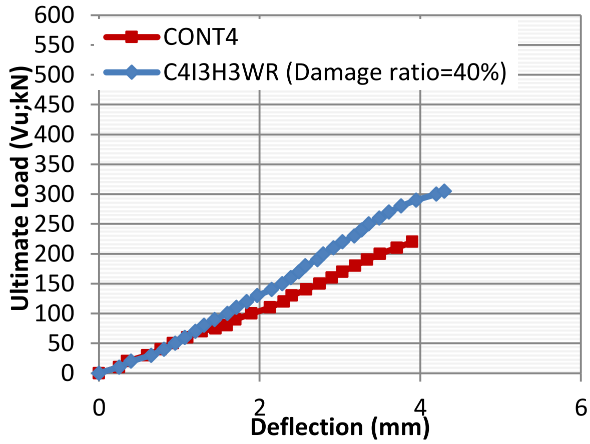


Figure 9: Load-Deflection Curves for Repaired Corbel $C_4I_3H_3WR$ without Secondary Reinforcement

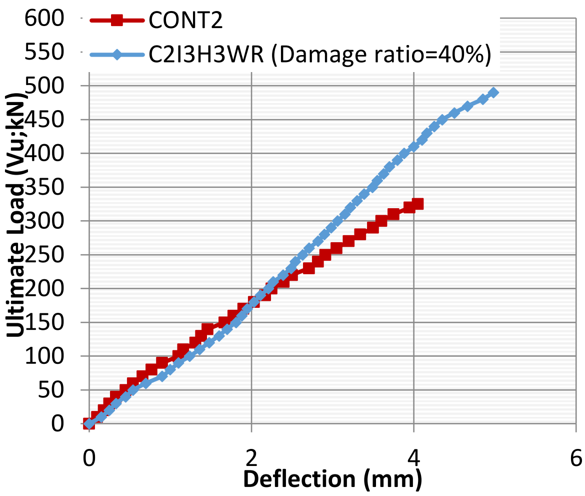


Figure 10: Load-Deflection Curves for Repaired Corbel $C_2I_3H_3WR$ with Secondary Reinforcement (2Ø6mm)

7. Crack Pattern and Failure Mode

The presence of CFRP, not only increase the ultimate strength of the SCC corbels, but gives another advantage; it shift the cracking from several widely spaced and large width cracks to many more closely spaced narrower cracks, and reduced the corbel deflection at same load level.

It has been found that the application of CFRP strips restrained the cracking propagation; however the quantity, position, direction and bonding type of the CFRP strips had been found to have a great effect on the crack pattern as shown in Figure 11. The specimens (C_1H_1F, C_1H_2F, C_1H_3F, C_1H_4F, C_1I_1F, C_1I_2F and C_1I_3F) failed by de-bonding of one (or more) CFRP strip at free end of strengthened. Also the locations of de-bonding differ in the specimens that had increased bond strength (i.e. C_1H_3W and C_1I_3W), the de-bonding was at the mid- span of the specimen, except C_1V_4W failed by rupture the CFRP strip. While for other specimens, that had used optimum strengthened method by CFRP strips failed by de-bonding and rapture of CFRP strips especially at mid span and strut of specimen.

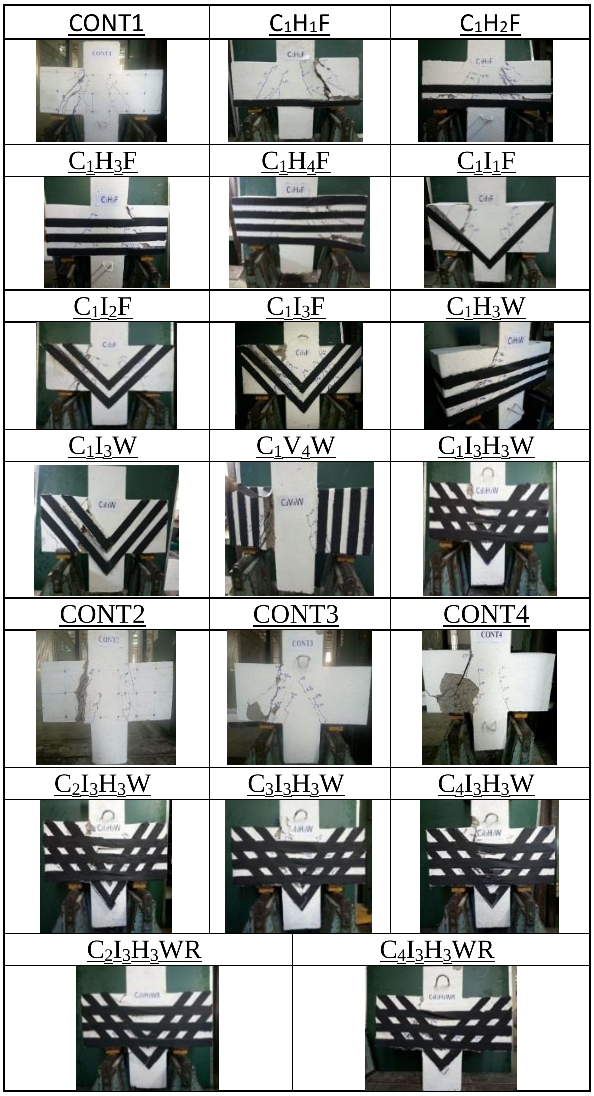


Figure 11: Crack pattern after failure for all corbels specimens

8. Conclusions

1. Using CFRP strips is an effective technique for strengthening SCC corbels. It can increase the ultimate load capacity from about (19 to 88) % and increase in cracking load reach to (93) %, also present stiffer load deflection response than un-strengthened corbels (control corbels).

2. The distribution, direction, location, bonding type and amount of CFRP strips play an important role in improving the stiffness, cracking and ultimate loads. It was found that strengthening corbels by inclined and horizontal direction by CFRP strips gives best results if compared with strengthened in vertical direction.

3. The effect of strengthening by CFRP in horizontally placed strips is greatly dependent on position of application to improve ultimate load. The horizontal CFRP strips when distributed at (2d/3) measured from bottom edge of the main tension reinforcement, give same improve in comparison with presence horizontal CFRP strip in the upper edge of corbel [more than(2d/3)] as recommended in ACI code about distribution of secondary reinforcement stirrups.

4. Specimens that wrapping by CFRP strengthening strips as U or ∩ shape and as a box shape have a better effect in stiffness and additional increasing of cracking load (increase serviceability) reach to 13%, while additional increase reach to 9% in ultimate load as compared to specimens that strengthened in two side.

5. The cracking and ultimate loads for un-strengthened corbels increase by (33.33%) and (35.41%) respectively as the shear span to effective depth ratio (a/d) decreases from 0.65 to 0.4 at same with same horizontal secondary reinforcement stirrups. Also the failure mode change from diagonal splitting to shear failure.

6. For strengthening corbels with optimum result of strengthening with same horizontal secondary reinforcement stirrups, the cracking and ultimate loads increase by (55%) and (28.88%) when the (a/d) ratio decreases from 0.65 to 0.4. The strengthened specimens having same failure with varied a/d ratio by de-bonding and rupture the CFRP strips exactly at mid span and strut (from support to upper corner of column-beam junction).

7. The increase in the amount of horizontal steel reinforcement stirrups with same a/d ratio for un-strengthened corbel from zero to 1Ø6mm cause an increase in cracking and ultimate loads by (15.38)% and (18.18)% respectively. When the amount of horizontal steel reinforcement stirrups increases from 1Ø6mm to 2Ø6mm the increase by (6.66%) and (25%) for cracking and ultimate loads respectively. Also the cracking and ultimate loads increases by (23.07%) and (47.72%) when the horizontal steel reinforcement stirrups increase from zero to 2Ø6mm. In addition to, the increase in horizontal steel reinforcement stirrups change the mode of failure from diagonal splitting to shear failure.

8. For strengthening corbels with optimum result of strengthening with same a/d ratio, the increase in the amount of horizontal steel reinforcement stirrups from zero to 1Ø6mm causes an increase in cracking and ultimate loads by (21.73) and (18.42%) respectively. When the amount of horizontal steel reinforcement stirrups increases from 1Ø6mm to 2Ø6mm the increase by (10.71%) and (28.88%) for cracking and ultimate loads respectively. Also the cracking and ultimate loads increases by (34.78%) and (52.63%) when the horizontal steel reinforcement stirrups increase from zero to 2Ø6mm. The strengthened specimens having same failure with varied amount of horizontal steel reinforcement stirrups by de-bonding and rupture the CFRP strips exactly at mid span and strut (from support to upper corner of column-beam junction).

9. For the corbel with horizontal steel reinforcement stirrups (2Ø6mm) and repaired at damage ratio (40% of ultimate load of control specimen CONT2) with optimum result of strengthening, the increase in ultimate load reach to (50.76%) with respect to ultimate load of control specimen. While for corbel that without horizontal steel reinforcement stirrups and repaired at damage ratio (40% of ultimate load of control specimen CONT4) with same optimum result of strengthening that present above, the increase in ultimate load reach to (38.63%) with respect to ultimate load of control specimen.

10. The de-bonding for strengthened corbels (which is the main mode of failure) is sudden and has a brittle nature. A few sounds were the only warning of the de-bonding that indicates high forces in the CFRP strips.

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