ULTIMATE SHEAR STRENGTH OF REINFORCED HIGH STRENGTH CONCRETE CORBELS SUBJECTED TO VERTICAL LOAD

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Abstract

The present investigation examines experimentally the behavior and ultimate shear strength of reinforced high-strength concrete corbels subjected to vertical load. The experimental investigation consist of casting and testing fourteen reinforced high-strength concrete corbels, the main variables studied were concrete compressive strength (40 to 62 MPa), main reinforcement ratio (0.517 %, 0.776 % and 1.034 %), shear reinforcement stress ($\rho_h f_{yh}$=1.535, 2.305 and 3.071 MPa), and the ratio of outside depth to the total depth of the corbel (k/h= 0.24 to 1.00).

The results indicate that high-strength concrete corbels (f_c'= 40 to 62 MPa) behaved similarly to those made with normal strength concrete, the increase in compressive strength of concrete leads to increase in ultimate shear strength with ductile failure. By increasing f_c' from 40 to 62 MPa for $\rho_h.f_{yh}$ equal to 1.535 MPa and 2.305 MPa, the ultimate shear strength increased by about 20.8% and 27.5% respectively. An increase in ρ_w by about 100% caused an increase in load carrying capacity by about 27.7%. Also by increasing $\rho_h.f_{yh}$ by about 100%, the ultimate shear strength increased by about 14.7% and 11.1% for corbels with f_c' equal to 40 and 49 MPa respectively, while for corbels with f_c' equal to 62 MPa, an increase in horizontal shear reinforcement stress ($\rho_h.f_{yh}$) by about 50% caused an increase in ultimate shear strength by about 12.3%, and this indicate that the contribution of horizontal stirrups in increasing ultimate shear strength was more efficient for corbels having compressive strength equal to 62 MPa. As (k/h) increased from 0.24 to 1.00, the ultimate shear strength increased by 11.5%.

Keywords: **Corbel, high strength concrete, shear strength, strut and tie model.**

مقاومة القص القصوى للكتائف الخرسانية المسلحة عالية المقاومة المعرضة للحمل العمودي

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الخلاصة

هذا البحث يفحص عمليا مقاومة القص القصوى للكتائف (Corbels) الخرسانية المسلحة عالية المقاومة و المعرضة الى الحمل العمودي. يشمل البحث العملي صب و فحص اربعة عشرة نماذج من الكتائف الخرسانية المسلحة عالية المقاومة. المتغيرات الاساسية التي درست هي مقاومة الانضغاط للخرسانة (f_c') (من 40 MPa الى 62 MPa) و نسبة التسليح الرئيسى (ρ_w من 0.517% الى 1.034%) و اجهاد تسليح القص ($\rho_h f_{yh}$ من 1.535 MPa الى 3.071 MPa) و نسبة العمق الخارجي الى العمق الكلي للكتائف (k/h من 0.24 الى 1.00).

بينت النتائج بان سلوك الكتائف الخرسانية المسلحة عالية المقاومة (f_c'= 40 to 62 MPa) مشابه لسلوك الكتائف المصنعة من الخرسانة العادية, زيادة مقاومة الانضغاط للخرسانة تؤدي الى زيادة مقاومة القص للكتائف دون حصول فشل مفاجيء, فزيادة مقاومة الانضغاط للخرسانة من من 40 MPa الى 62 MPa تزيد من مقاومة القص بمقدار 20.8% للكتائف ذات $\rho_h f_{yh}$ مساوي الى 1.535 MPa و بمقدار27.5% للكتائف ذات $\rho_h f_{yh}$ مساوي الى 2.305 MPa. ايضا زيادة نسبة التسليح الرئيسي (ρ_w) بمقدار 100% تؤدي الى زيادة مقاومة القص بمقدار 27.7%. و تبينت من الدراسة بان مساهمة تسليح القص لزيادة مقاومة القص اكثر فعالية للكتائف ذات (f_c'=62 MPa) بالمقارنة مع الكتائف الاخرى ذات (f_c'=40 or 49 MPa), فزيادة قيمة $\rho_h f_{yh}$ بمقدار 100% تؤدي الى زيادة مقاومة القص بمقدار 14.7% للكتائف ذات (f_c'=40 MPa) و بمقدار 11.1% للكتائف ذات (f_c'=49 MPa), بينما زيادة قيمة $\rho_h f_{yh}$ بمقدار 50% للكتائف ذات (f_c'=62 MPa) ادت الى زيادة مقاومة القص بمقدار 12.3%. كما وتبين من النتائج ان زيادة قيمة (k/h) من 0.24 الى 1.00 تؤدي الى زيادة مقاومة القص بمقدار 11.5%.

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Introduction

Corbels are short cantilever deep beams with shear span to depth ratio less than unity(1). Corbels (or brackets) are usually built monolithically with columns, and they are project from the face of columns to support heavy concentrated load. Corbels are designed mainly to provide for the vertical reaction V_u at the end of the supported beam, but unless special precautions are taken to avoid horizontal forces caused by restrained shrinkage, creep, or temperature change, they must also resist a horizontal force N_u(2) .

According to ACI committee 363(3), High-Strength concrete (HSC) is a concrete having cylinder compressive strength for the design greater than 41 MPa and it excludes concrete made using exotic material or techniques. HSC is very often used in recent years because HSC offers many advantages over conventional concrete(3,4).

With the production of HSC, enhanced properties of concrete can be achieved. However, since high-strength concrete is typically more brittle than normal strength concrete, it should be ensured that higher strength can be used without leading to catastrophic brittle failure. Most of the existing research on the behavior of corbel deals only with normal strength concrete (5,6,7,8). Also most code provisions are based on the results obtained using concrete with cylinder compressive strength less than 40 MPa(9).

In 1985 yong et al(10) carried out test on 8 High-strength concrete corbels, with total height of 406 mm, length of projection from the column 254 mm, Width of 254mm and shear span to depth ratio (*a/d*) equal to 0.39. The variables were the amount of main reinforcement and compressive strength of concrete. Two of the eight corbels which had no steel reinforcements had shear failure at the interface of the corbel and the column, and the failure was sudden. The other six specimens which had main and shear reinforcement was failed in a beam-shear as defined by Mattock, Chen and Soonswong(6). From the result of the test they conclude that ACI Code 1983(11) provisions are conservative, increase in concrete compressive strength is not fully utilized in the corbels designed according to the ACI code 1983 provisions, and for shear span to effective depth ratio equal to 0.393 which is used in this test, the ACI 318-83 imposed limit of shear strength V_n to 5.5 *b.d* results in a design area of main reinforcement as that always falls below the minimum required area if the concrete compressive strength is greater than 65.7 MPa.

In 1994 Yong Y. and Balguru P.(9) tested a total of sixteen high-strength concrete corbels two of which were un reinforced. The primary variables of the investigation were presence of horizontal force, reinforcement ratio and shear span-to-depth ratio *(a/d)*. The failure of the fourteen reinforced corbels was stable and ductile, and classified as beam-shear failure(6). The major difference between the corbels subjected to vertical load only and those subjected to both vertical and horizontal loads were in the area of secondary cracks and the spalling of the concrete between the cracks. The experimental results obtained in this investigation are compared with prediction based on the equations specified in ACI 318-89, and the truss analogy method proposed by Hagberg(12). They state that ACI 318-89 procedure leads to an conservative prediction of strength. In general, the truss analogy method by Hagberg provided better predictions of shear strength for the tested corbels as compared to the ACI 318-89 procedure.

Foster et al(13) tested 30 high-strength concrete corbels, the main variables were concrete compressive strength, shear span to effective depth ratio, and the provision of secondary reinforcement. Based on the test results they concluded that:

1. The first cracks are flexural cracks propagating from the corbel-column intersection,
2. Corbel fabricated from HSC behaved similarly to those made of normal-strength concrete (NSC).
3. Providing secondary reinforcement reduced crack widths, improved ductility, and for beams failing in splitting to compression strut crushing. A minimum quantity of

horizontal stirrups similar to that for normal strength concrete should be used in HSC corbels.

4. The ACI 318-89 design method is not recommended for use with corbels designed with high and very high-strength concrete.

Ali et al(14) carried out tests on 13 reinforced high-strength concrete corbels without stirrups. The variables included in this study were (*a/d*) ratio and size of the corbel (d). d varied from 71 to 292.5mm and *a/d* varied from 0.25 to 0.7. The test results compared with the value of shear strength capacity predicted using equations proposed by kriz and Raths(5), Solanki and Sabinis(15), Siao(16), and the ACI 318-99. The results showed that for geometrically similar specimens, the unit shear stress at failure, v_u for small specimens is higher than that of large specimens. (i.e. the small depth specimens behaved better than the larger one) also the test results indicated a significant size effect on the shear failure of the corbels, and that the safety factor for the larger corbel was lower than the similar smaller corbels. The available methods used for predicating the ultimate shear strength of corbels failed to meet a wide range of depth (size) for which the design is safe, except the ACI 318-99 method which is better than the others in this field.

This investigation is mainly concerned with studying the strength and behavior of reinforced high-strength concrete corbels with main tension bars and horizontal stirrups as shear reinforcement. Parameters of this study include concrete compressive strength, main and secondary reinforcement ratio, and the *k/h* ratio.

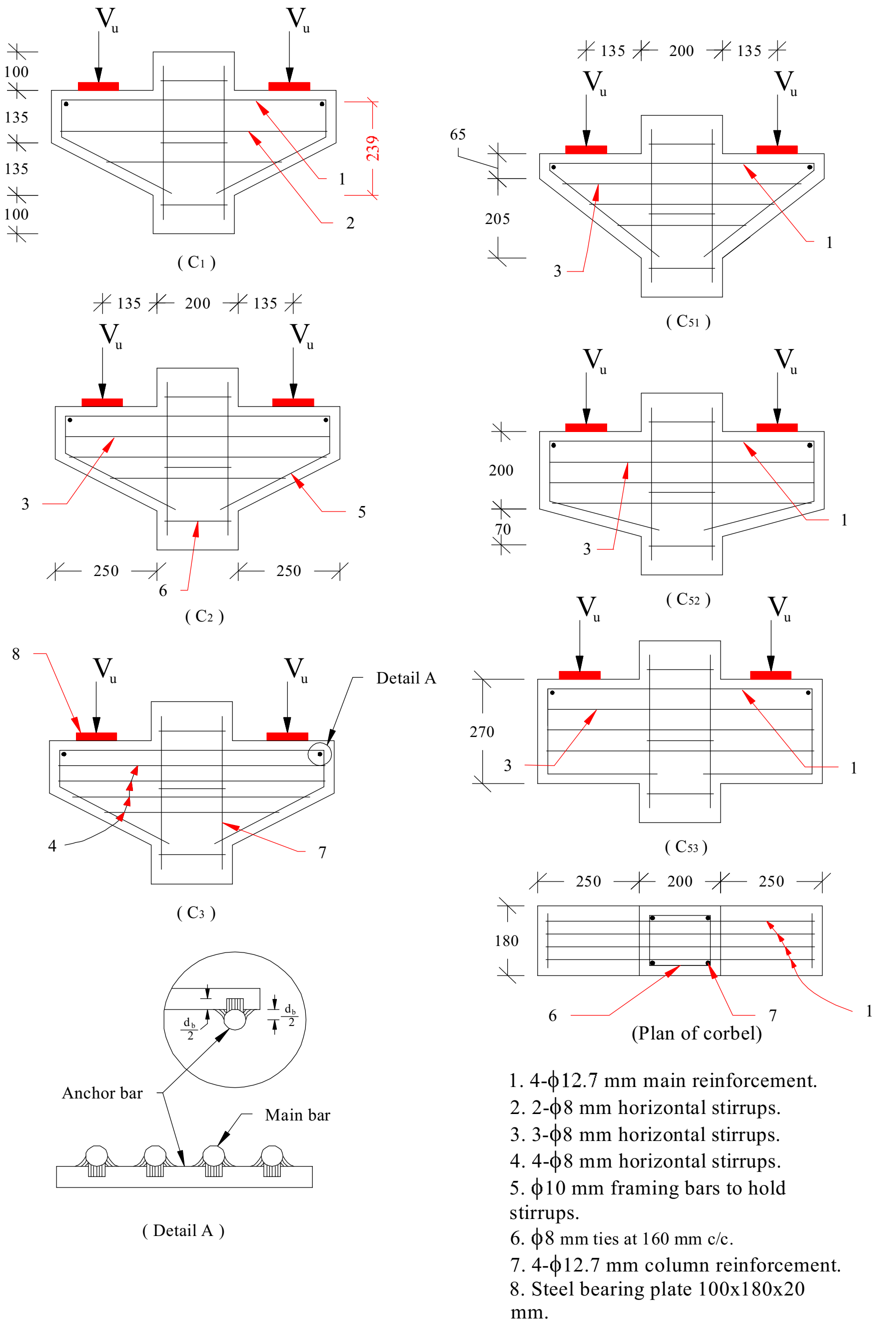
Experimental Program

The details of reinforcement and dimensions of corbel specimens are shown in Table (1) and Fig.(1). Each corbel was identified by the label C_{xn}, where the letter (C_x) denotes the group and (n) denotes the number of the tested corbel. The tested corbels were divided into five groups: C_1, C_2, C_3, C_4 and C_5. The main parameters studied in this investigation were concrete compressive strength, amount of shear reinforcement ratio (groups C_1-C_3), flexural reinforcement ratio (group C_4) and the ratio of outside depth to the total depth of the corbel (group C5).

Table (1) Detail of tested reinforced concrete specimens

Group No.	Specimen No.	f'_c MPa	$\rho_h.f_{yh}$ MPa	ρ_w %	*k/h*	Detail of reinforcement	
						Stirrups	Main bars
1	C_{11}	40	1.535	1.034	0.5	2-Ø8 mm	4-Ø12 mm
	C_{12}	50					
	C_{13}	60					
2	C_{21}	40	2.305	1.034	0.5	3-Ø8 mm	4-Ø12 mm
	C_{22}	50					
	C_{23}	60					
3	C_{31}	40	3.071	1.034	0.5	4-Ø8 mm	4-Ø12mm
	C_{32}	50					
	C_{33}	60					
4	C_{41}	50	2.305	0.517	0.5	3-Ø8 mm	2-Ø12 mm
	C_{42}			0.776			3-Ø12 mm
5	C_{51}	50	2.305	1.034	0.24	3-Ø8 mm	4-Ø12 mm
	C_{52}				0.74		
	C_{53}				1.00		

-Note: shear span-to-effective depth ratio *(a/d)* equal to 0.565 for all corbel specimens.



1. 4-ϕ12.7 mm main reinforcement.
2. 2-ϕ8 mm horizontal stirrups.
3. 3-ϕ8 mm horizontal stirrups.
4. 4-ϕ8 mm horizontal stirrups.
5. ϕ10 mm framing bars to hold stirrups.
6. ϕ8 mm ties at 160 mm c/c.
7. 4-ϕ12.7 mm column reinforcement.
8. Steel bearing plate 100x180x20 mm.

Fig.(1) Detail of the corbel and reinforcement.

Materials

The cement used in this investigation was Turkish Portland cement type I (P.C. type I). The fine and coarse aggregate (sand and gravel) obtained from Aski Kalak which is commonly used in Erbil Governorate, there grading satisfies ASTM C33 specification. The maximum size of the coarse aggregate was 9.52 mm. The Glenium admixture (GLINUM ACE 30) was used in specimens C_{13}, C_{23} and C_{33} by 0.5% of the weight of cement.

Deformed bars of diameters 12 mm (f_y=415 MPa) were used for the main tension reinforcement for the corbels and as longitudinal reinforcement in the column, also it is used as cross bars to anchor the main steel at the ends of the corbels. Deformed bars of diameter 8 mm (f_y=415 MPa) were used for shear reinforcement in the corbel and as ties in the column, 10 mm diameter deformed bars used as framing bars to support the stirrups.

Mix Details and Proportions

Mix proportion for production of high strength concrete requires more quality control than normal strength concrete (NSC). The mix proportion selected from suitable ingredients of concrete with relative quantities in order to meet the requirement of stronger concrete with suitable workability. Two mix proportions selected from suitable test investigation to obtain a suitable different compressive strength. The third mix proportion used in this project is the same proportion of second mix with adding admixture (GLINUM ACE 30). The detail of the mix proportions is shown in Table (2).

Table (2) Mixes properties

No.	Mix proportion C:S:G	W/C Ratio	Ad/C ratio
1	1:1.23:1.87	0.36	---
2	1:1.05:1.625	0.325	---
3	1:1.05:1.625	0.28	0.005

The following equation can be solved for the total aggregate weight, knowing the weight of cement, water and bulk specific gravity of the material.

$$\frac{w_w}{\gamma_w}+\frac{w_c}{\gamma_c}+\frac{w_s}{\gamma_s}+\frac{w_g}{\gamma_g}+\frac{w_{ad}}{\gamma_{ad}}=1000 \qquad .....(1)$$

Where :

w_w, w_c, w_s, w_g and w_{ad} are weight of water, cement, sand, gravel and admixture respectively.

$\gamma_w, \gamma_c, \gamma_s, \gamma_g$ and γ_{ad} are the bulk specific gravity of water, cement, sand , gravel and admixture respectively.

Mixing Method, Casting and curing

The mixing procedure is important for obtaining the required workability. A digital controlled rotary mixer of (1 m^3) capacity was used. The interior surface of the mixer was cleaned and moistened before placing the materials. Initially the fine and coarse aggregates were poured in the mixer, followed by 25% of the mixing water to wet them. Afterwards the cement was added. Finally the remaining 75% of the mixing water (with admixture for the third mix proportion) was added gradually to the mix, and the mixing operation was continued until homogenous concrete was obtained.

Casting was started by placing the concrete inside the molds using a trowel. A concrete mix was placed in two layers and each layer was vibrated about 20 seconds using internal vibrator in four locations, the process of vibration has been continued for the final layer until no further air bubbles appeared on the surface.

As casting was completed, the top surface of the specimens was thoroughly finished with a steel trowel. The forms were covered with damp canvas cloth and left for about 24 hours. The specimens were then remolded carefully and covered with damp canvas for about 28 days, after that left in air temperature and humidity until date of testing.

Testing

The corbels were tested by a universal testing machine of 100 ton (981 kN). A mechanical method has been used for measuring the tensile strain of the main tension bars. The strain was measured at location of maximum negative moment at the column-corbel junction, as shown in Fig.(2).

All the corbels were tested at age of 56 days. Two days before testing, the corbels were painted (white) in order to help in locating cracks and taking photographs. The corbels were tested in an inverted position, as shown in Fig.(3) the vertical load was applied at the top end of the column using a universal hydraulic testing machine. The corbel was seated on steel roller supports with horizontal surface of the corbel in order to get a shear span-to-depth ratio (*a/d*) equal to 0.565. The dial gauge was placed in its marked position.

An incremental stage loading was applied in order to obtain a continuous view of the performance of each corbel. The load was increased by equal increment of one ton (9.81 kN). At each load stage the deflection and strains were recorded and a search was made for the appearance of any cracks. The positions, magnitude, and extents of the first and other consequent cracks were marked. As the failure was reached, the failure load was recorded, and the load was removed to allow taking some photographs of the final crack patterns.

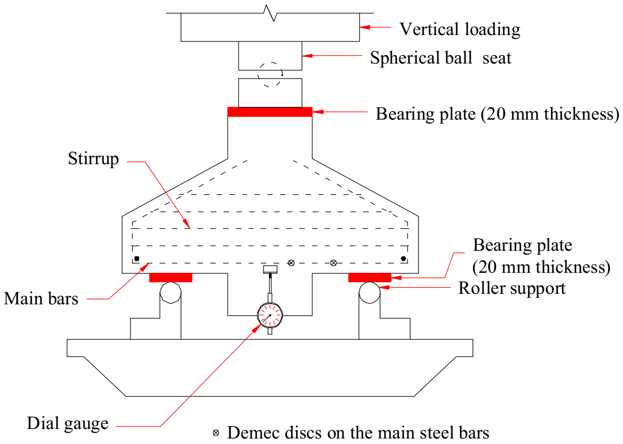


Fig.(2) Loading arrangement with location of demec discs and dial gauge.

Fig.(3) Loading machine and test setup.

Results of the Tested Specimens and Discussion

The experimental results of the tested corbels are listed in Table (3). The following sections show the effect of different parameters on the behavior of reinforced high-strength concrete corbels.

Effect of Compressive Strength of Concrete

The ultimate shear strength increased by about 20.8% and 27.5%, were concrete compressive strength increased from about 40 MPa to 62 MPa, for $\rho_{h,}f_{yh}$ values equal to 1.535 and 2.305 MPa respectively. Fig.(4) shows the effect of compressive strength on ultimate shear strength of the tested corbels.

Effect of Main tension reinforcement ratio

The effect of main tension reinforcement ratio (ρ_w) on load carrying capacity is shown in Fig.(5), an increase in main tension reinforcement ratio by about (100%) caused an increase in load carrying capacity by about (27.7%). With increasing (ρ_w) the ductility of the corbel increased, the flexural crack has a larger width and length along the column-corbel interface when (ρ_w) increased.

Table (3) Test results of the corbel specimens

Group No.	Specimen No.	f'_c * MPa	$\rho_h.f_{yh}$ MPa	ρ_w %	k/h	$V_{cracking}$ kN	V_u kN
1	C_{11}	41.5	1.535	1.034	0.5	63.7	350.6
	C_{12}	48.8				71.6	382.8
	C_{13}	61.4^{**}				83.4	423.6
2	C_{21}	40.1	2.305	1.034	0.5	67.7	373.1
	C_{22}	51.3				78.5	405.8
	C_{23}	62^{**}				88.3	475.6
3	C_{31}	38.8	3.071	1.034	0.5	75.0	402
	C_{32}	46.4				85.8	425.2
	C_{33}	63.5^{**}				98.1	$> 475.6^{***}$
4	C_{41}	48.3	2.305	0.517	0.5	58.8	317.8
	C_{42}	50.2		0.776		69.6	350.8
5	C_{51}	51.6	2.305	1.034	0.24	78.5	382.7
	C_{52}	50.7			0.74	78.9	417.3
	C_{53}	49.3			1.00	79.4	426.8

* f_c' is taken as (0.8 x Cube compressive strength).

** Concrete with admixture.

*** The specimen not failed (maximum capacity of the loading machine was 2 x 490.3 kN).

Effect of Horizontal Shear Reinforcement Index

An increase in horizontal shear reinforcement index ($\rho_{h,}f_{yh}$) by about 100% caused an increase in ultimate shear strength by about 14.7% and 11.1% for concrete compressive strength equal to about 40 and 49, while for concrete compressive strength of 62 MPa, an increase in horizontal shear reinforcement index ($\rho_{h,}f_{yh}$) by about 50% caused an increase in ultimate shear strength by about 12.3% as shown in Fig.(6). This indicate that the contribution of shear reinforcement stress in increasing ultimate shear strength of the corbels was more efficient for corbels with (f_c'=62 MPa) than corbels having a smaller (f_c').

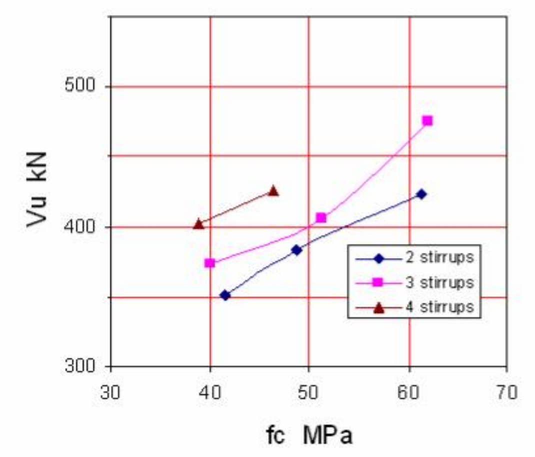


Fig.(4)Shear strength versus f_c'.

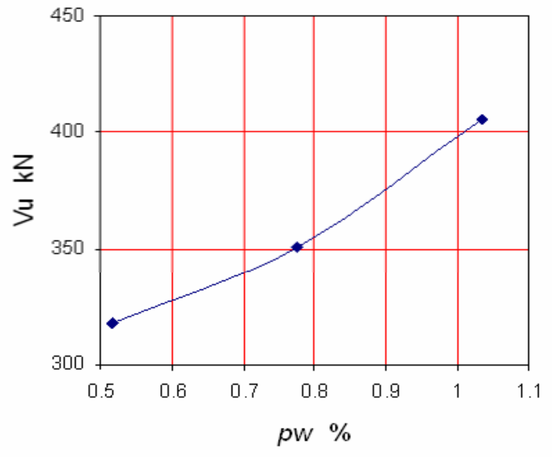


Fig.(5) Shear strength versus ρ_w.

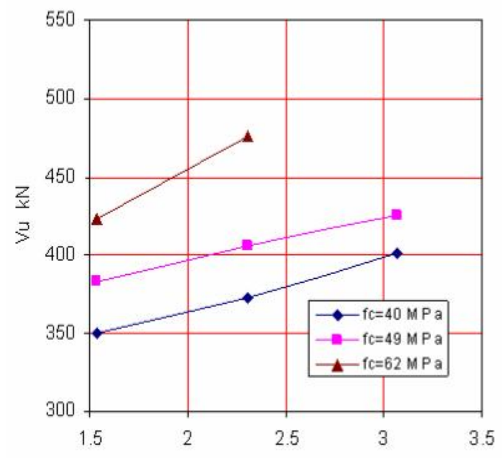


Fig.(6) Shear strength versus $\rho_h.f_{yh}$.

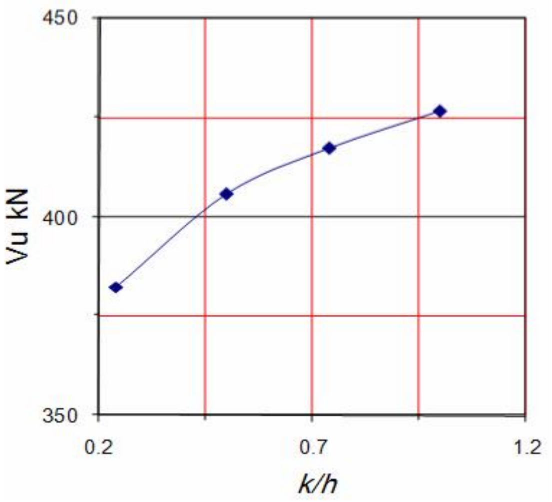


Fig.(7) Shear strength versus *k/h*.

Effect of The ratio of out side depth to total depth (k/h)

As (*k/h*) increased from 0.24 to 1.00, the ultimate shear strength increased by 11.5%, the effect of (*k/h*) on ultimate shear strength is shown in Fig.(7). The diagonal tension crack in corbel C_{51} which has the smallest ratio of *(k/h)* followed a more curved path to the sloping face of the corbel.

Load-Deflection curves

Load-deflection curves for the tested corbels are shown in Figs.(8) through (12). The deflection represent the movement of the loading jack (i. e. average deflection of the two corbels of each specimen at the supports). Each one of these curves is initiated in a linear form with constant slope. Then, it changes to nonlinear form with varying slope, as shown in the Fig.(8) through (12). For the same applied load the deflection decreased due to increasing the compressive strength of concrete, the amount of reinforcement (both longitudinal bars and horizontal stirrups) and the ratio (*k/h*).

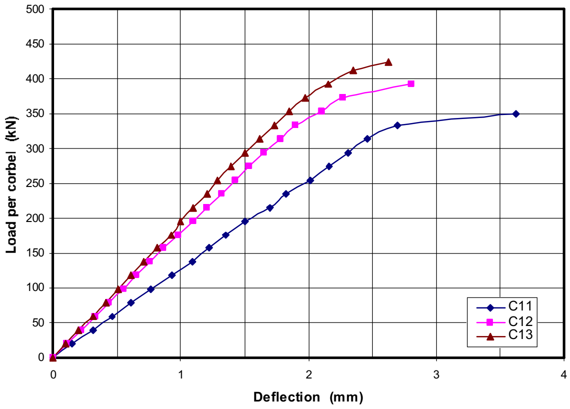


Fig.(8) Load deflection curves for corbels in group one.

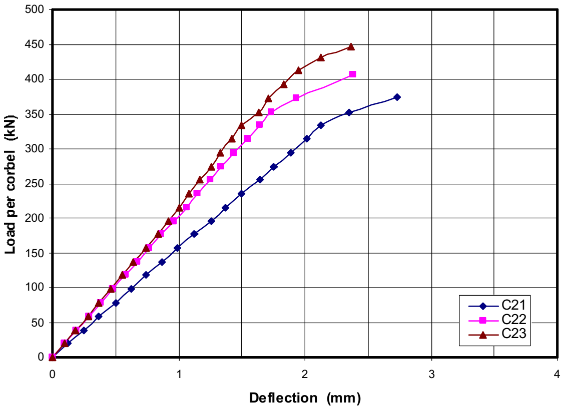


Fig.(9) Load deflection curves for corbels in group two.

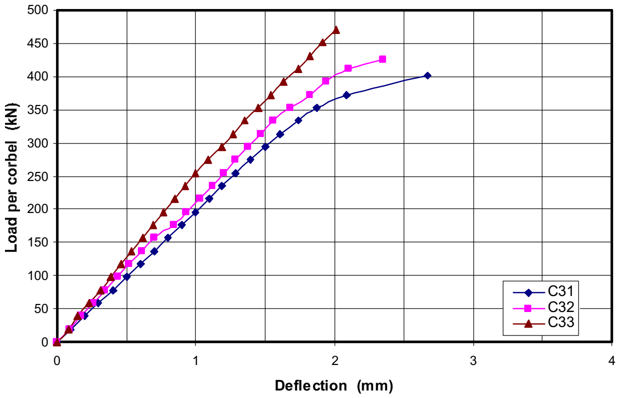


Fig.(10) Load deflection curves for corbels in group three.

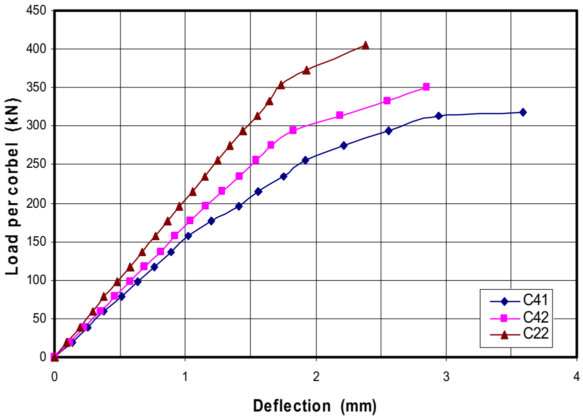


Fig.(11) Load deflection curves for corbels in group four.

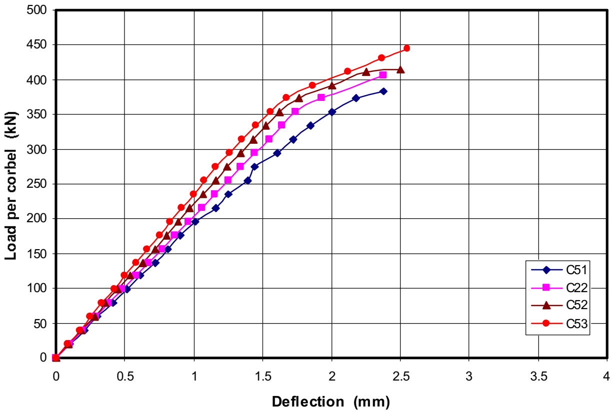


Fig.(12) Load deflection curves for corbels in group five.

Strain in Main Reinforcement

For all the tested corbels the main steel bars yielded before the maximum load was reached. Figs.(13) through (15) show the effect of various parameters which is studied in this research on the main bar strain. As shown in the figures for all the tested corbels first the curves was steepest, terminated at the occurrence of the first flexural crack. After the initiation of the first crack, the strain increased rapidly for a small load increment.

Cracking Load

The first cracks to form were flexure crack which propagated from the intersection of the column face and the horizontal face of the corbel. The first crack loads for the tested corbels are listed in Table (3).

For corbels having the same compressive strength, first cracking load increased as the number of horizontal stirrups or main bars increased, also with increasing the compressive strength the first cracking load increased.

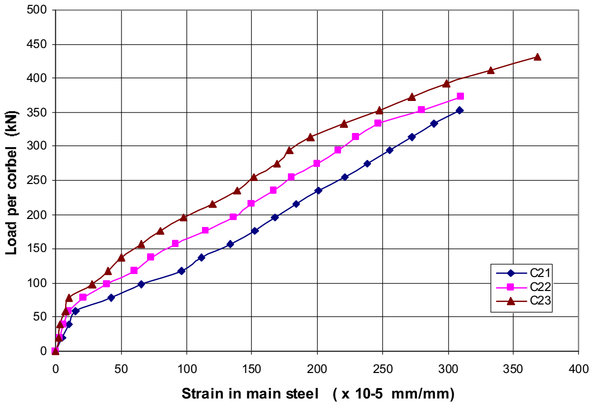


Fig.(13) Effect of concrete compressive strength on main steel strain for corbels with $\rho_h.f_{yh}$=2.305.

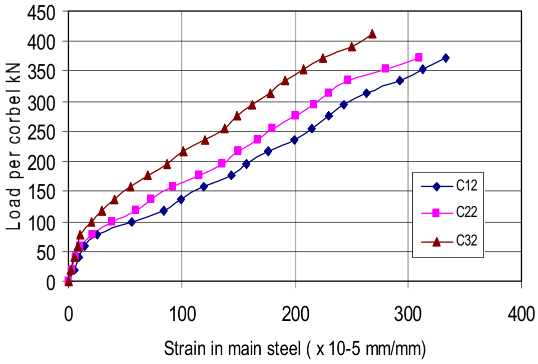


Fig.(14) Effect of $\rho_h.f_{y\,h}$ on main steel strain.

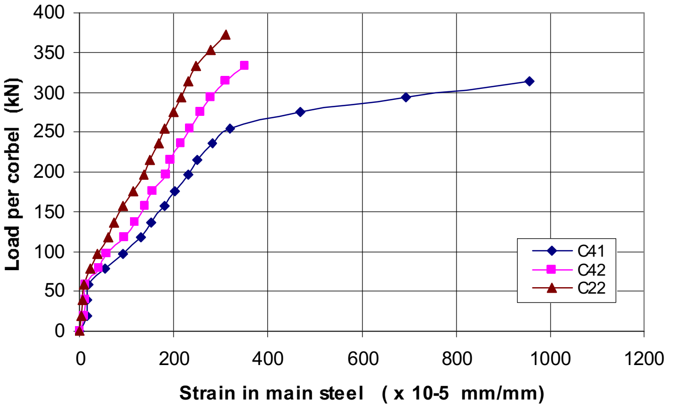


Fig.(15) Effect of ρ_w on main steel strain.

Crack Pattern and Modes of Failure

The tested corbels in group one, two and three have a similar failure pattern (Fig.16), for the specimen C_{33} loading was stopped at load of about 475.6 kN and the corbel not failed (the ultimate shear strength of this corbel specimen was more than the capacity of the loading machin). First, a flexural crack initiated at the reentrant corner, after formation of this cracks the tension reinforcement stress increased much more rapidly. While this crack was propagated along the column-corbel interface, a diagonal tension cracks appeared in the corbels. These cracks run among a point between the inner edge of the bearing plate and the point of intersection of the sloping face of the corbel and column face. This cracks become the major crack which caused the failure. The failure was stable and ductile and could be classified as beam-shear failure which defined by Mattock et al(6). In this type of failure the flexural cracks remained fine and failure was characterized by widening of one or more diagonal tension cracks and the shear-compression failure of the concrete near the intersection of the sloping face of the corbel and the column face.

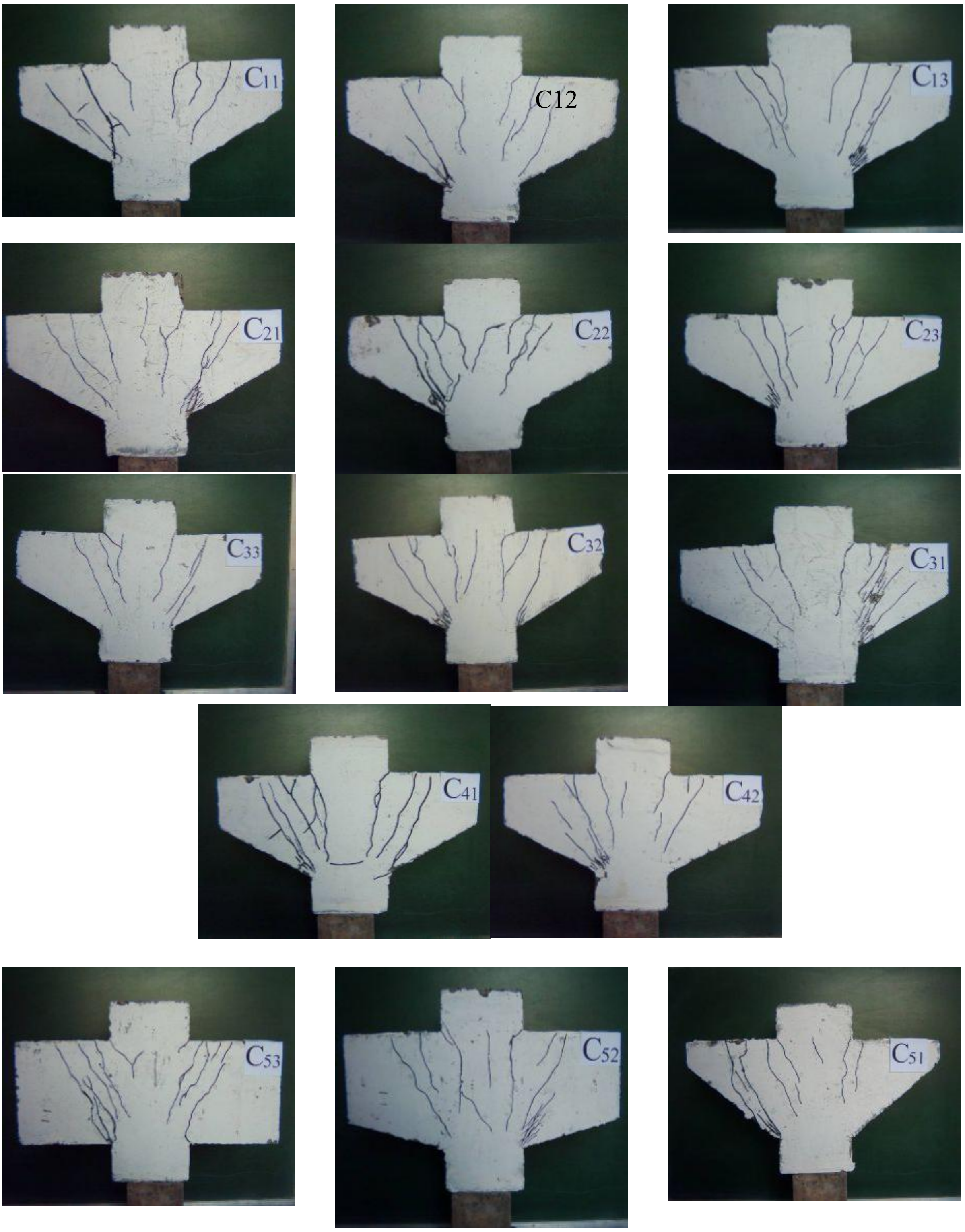


Fig.(16) Crack pattern of the tested corbels.

In group four where amount of longitudinal reinforcement changed, for corbel C_{42} which has 3 Ø12mm as main reinforcement (ρ_w=0.776%), the width of flexural crack was more than those for corbels having 4 Ø12mm main reinforcement (ρ_w=1.034%). But also this corbel failed in beam-shear as described before .Corbel C_{41} having only 2 Ø12mm as main reinforcement (ρ_w=0.517%) failed in flexural tension, the failure occurs by crushing of the concrete at the bottom of the sloping face of the corbel after extensive yielding of the tension reinforcement. flexural tension failure characterized by a very wide flexural crack. The failure of this corbel was more ductile than corbel failed in beam-shear. Also the three corbels (C_{51},C_{52} and C_{53}) in group five which having various (k/h) ratio failed in beam-shear as described earlier, but the difference in crack pattern can be noted in corbel C_{51}. The diagonal tension crack in corbel C_{51} followed a more curved path to the sloping face of the corbel.

Conclusions

Based on the experimental results of this investigation the following conclusions can be drawn:

1. All corbels in group one, two, three (except C_{33}), five, and corbel C_{42} failed in beam-shear. the failure was stable. Corbel C_{41} failed in flexural tension, the failure was stable and more ductile than the other corbels which failed in beam-shear.
2. Increasing in reinforcement ratio (ρ_w and ρ_h) and (k/h) leads to increase in corbel stiffness and ultimate shear strength.
3. The behavior of high-strength concrete corbels is similar to that of normal strength concrete corbels. The increase in compressive strength (f'_c) leads to increase the load carrying capacity of the corbels but dose not caused brittle failure of the corbels.
4. The increase in shear reinforcement index ($\rho_h.f_{yh}$) was more efficient for corbels with (f'_c=62 MPa) than corbels with (f'_c=40 or 49 MPa).

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