Experimental Investigation on the Behavior of Reinforced Concrete Corbels under Repeated Loadings

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Abstract

In this study, a total of twenty four vibrated and self-compacting concrete (SCC) corbels with normal and high compressive strength have been cast and tested under vertical loading. All corbels had the same main steel area. Twelve of these were tested under monotonic loading until failure with the following variables: shear span to effective depth ratio, amount of the secondary reinforcement (horizontal stirrups bars), strength of concrete (normal and high strength) and the type of concrete (vibrated and SCC). Test results indicate that the use of SCC in corbels, results in improving the behavior and shear strength of the specimens from (8.2% to 14.2%).For vibrated normal and high strength concrete, it was found that when the shear span to effective depth ratio is decreased an increase occurs in cracking and ultimate loads. Also, for corbels having the same shear span to effective depth ratio, the increase in the amount of secondary reinforcement (horizontal stirrups bars) causes an increase in the cracking and ultimate loads. In addition, tests were carried out on the other twelve corbels subjected to repeated loading regime in order to study the behavior of corbels under different load levels (60%, 80% and 90%) of the ultimate load of reference corbels. The results show that the corbels indicated that repeated loading scheme always experienced some increase in the deflection during consecutive cycles, and failed in a rather more ductile manner as compared with corbels subjected to monotonic loading regime.

Keywords: ***Corbels, Experimental investigation, Reinforced concrete, Repeated loadings***

دراسة عملية لتصرف الكتائف الخرسانية المسلحة تحت احمال تكرارية

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الخلاصة

في هذه الدراسة تم صب 24 نموذجا من الكتائف الخرسانية المسلحة باستخدام خرسانة اعتيادية الرص وخرسانية ذاتية الرص ذات مقاومة اعتيادية ومقاومة عالية و تم فحصها تحت تاثير احمال عمودية فقط . تمتلك النماذج كافة نفس مساحة حديد التسليح الرئيسي. تم فحص 12 نموذجا منها تحت حمل احادي الاتجاه لحين الفشل لدراسة المتغيرات التالية : نسبة فضاء القص الى العمق الفعال،وكمية الحديد الثانوي (الاطواق الافقية)، مقاومة الخرسانة (اعتيادية او عالية) و نوع الخرسانة المستخدمة (الاعتيادية او ذاتية الرص). وقد اظهرت النتائج ان استخدام الخرسانة ذاتية الرص في الكتائف الخرسانية يعمل على تحسين تصرف ومقاومة القص للنماذج بنسبة تتروح بين 8.2% الى 14.2% .وجد من خلال البحث ان تقليل نسبة فضاء القص الى العمق الفعال يؤدي الى زيادة في مقاومة حمل التشقق والاحمال القصوى للخرسانة اعتيادية الرص و ذات المقاومة الاعتيادية.وجد ان زيادة مساحة حديد التسليح الثانوي (الاطواق الافقية) للكتائف المصنعة من الخرسانة الاعتيادية الرص والتي لها نفس فضاء القص الى العمق الفعال يؤدي الى زيادة في حمل التشقق و حمل الفشل النهائي. بالاضافة الى ما سبق ذكره، فقد تم فحص 12 نموذجا تحت تاثير الاحمال الشاقولية الدورية باتجاه واحد لدراسة سلوك هذه الكتائف تحت احمال دورية مختلفة كنسبة (60%و80%و90%) من حمل الفشل النهائي للنموذج المرجعي . وقد اظهرت النتائج ان الكتائف التي تتعرض لاحمال دورية تظهر معدلات انحراف اعلى مع زيادة مستوى الاحمال الدورية ، وتبين انها تفشل بشكل اكثر مطيلي عند مقارنتها بنماذج تم فحصها تحت حمل باتجاه واحد لغاية الفشل.

1.Introduction

Corbels are brackets that extend from the face of columns and they are extensively used in precast concrete construction to support primary beams and girders. The term "corbel" is generally restricted to short cantilevers having shear span to effective depth ratio less than unity. Such a small ratio causes the strength of corbels to be primarily controlled by shear, which is similar to deep beams [1]. Corbels are principally designed to resist the ultimate shear force applied to them by the beam, the ultimate horizontal and bending action due to beam shrinkage, creep, or temperature change [2]. These are review of early studies on the behavior of corbels

Foster, et al., in (1996) [3] tested thirty high strength concrete corbels. The variables considered in the investigation were shear span to depth ratio, concrete compressive strength (45 to 105) MPa and the provision of secondary reinforcement. The investigation examined corbel behavior in the context of the considered parameters and the experimental results were compared with the ACI Code 318-89 design method and the plastic truss model of Rogowsky and MacGregor.

Bourget, et al. in (2001) [4] tested seven high strength reinforced concrete corbels using concrete grade ranging from 70 MPa to 120 MPa. The behavior of tested specimens was characterized by the crack pattern and by LVDT and gauge measurements. The crack pattern shows that failure of the concrete strut is due to the propagation of cracks from supporting zones to the corbel- column interface which was close to the corbel slopping face, and the strut failed in diagonal splitting mode. In the other cases, the strut failure occurred after the failure of the remained healthy concrete zone close to the corbel slopping face.

Zrar, in (2005) [5] carried out tests on fourteen reinforced high strength concrete corbels. The main variables studied were concrete compressive strength which ranged from (40 to 62) MPa, main reinforcement ratio, shear reinforcement stirrups and the ratio of outside depth (at the end of the corbel) to the total depth of the corbel. Based on the experimental data, the behavior of high strength concrete corbels is similar to the behavior of those made of normal strength concrete.

Aziz and Othman, in (2010) [6] investigated experimentally the behavior and ultimate shear strength of high-strength reinforced concrete corbels subjected to vertical loads. The experimental investigation consisted of casting and testing fourteen high strength reinforced 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 (1.535, 2.305 and 3.071) MPa and the ratio of outside depth to the total depth of the corbel (0.24 to

1.00).The results indicated that high strength concrete corbels behaved in a manner similar to those made with normal strength concrete.

Al-Zahawi in (2011) [7] tested fifteen fibrous and non-fibrous reinforced concrete corbels with and without stirrups. All specimens had the same length, thickness and the amount of main reinforcement, and were subjected to concentrated vertical load. The variables were shear span to the effective depth ratio), the amount of carbon fibers and the presence and absence of horizontal secondary reinforcement.

2. Experimental Program

The program consists of testing twenty four corbels. Tested Corbel details are presented in Figure 1 and Table 1.

For all corbels, the overall corbel dimensions, column size and the main reinforcement were kept constants throughout the study. Column dimensions and reinforcement were designed to ensure that their behavior would exclude column failure. The corbel size was (150×250×250) mm and the dimensions of the column supporting two corbels on its opposite sides were (150×200×650) mm. The column was reinforced with four (φ12 mm) diameter bars, at the corners and 8 mm diameter closed ties spaced longitudinally at (140 mm) center to center. All corbels were reinforced with three (φ 12 mm) deformed steel bars, on the tension side (as main reinforcement).

The specimens have been divided into six groups (A, B, C, D, E and F). These groups were classified according to concrete type (vibrated or self compacting (SCC)), shear span to effective depth ratio (a/d), concrete compressive strength values (f_c') and amount of secondary horizontal reinforcement.

Table 1 Details of corbel specimens.

Group	Corbel designation	Loading regime	a/d	Horizontal reinf. A_h mm^2	Variable used	Strength of concrete	Type of concrete	Horizontal stirrups
A	LNC1	monotonic	0.5	113	Control	Normal	Vibrated	2- Ø 6 mm
	LNC2	repeated			90%	Normal	Vibrated	2- Ø 6 mm
	LNC3	repeated			80%	Normal	Vibrated	2- Ø 6 mm
	LNC4	repeated			60%	Normal	Vibrated	2- Ø 6 mm
B	LSCC1	monotonic	0.5	113	Control	Normal	SCC	2- Ø 6 mm
	LSCC2	repeated			90%	Normal	SCC	2- Ø 6 mm
	LSCC3	repeated			80%	Normal	SCC	2- Ø 6 mm
	LSCC4	repeated			60%	Normal	SCC	2- Ø 6 mm
C	HNC1	monotonic	0.5	113	Control	High	Vibrated	2- Ø 6 mm
	HNC2	repeated			90%	High	Vibrated	2- Ø 6 mm
	HNC3	repeated			80%	High	Vibrated	2- Ø 6 mm
	HNC4	repeated			60%	High	Vibrated	2- Ø 6 mm
D	HSCC1	monotonic	0.5	113	Control	High	SCC	2- Ø 6 mm
	HSCC2	repeated			90%	High	SCC	2- Ø 6 mm
	HSCC3	repeated			80%	High	SCC	2- Ø 6 mm
	HSCC4	repeated			60%	High	SCC	2- Ø 6 mm
E	LNC5	monotonic	0.7	113	a/d	Normal	Vibrated	2- Ø 6 mm
	LNC6	monotonic	0.3		a/d	Normal	Vibrated	2- Ø 6 mm
	HNC5	monotonic	0.7	113	a/d	High	Vibrated	2- Ø 6 mm
	HNC6	monotonic	0.3		a/d	High	Vibrated	2- Ø 6 mm
F	LNC7	monotonic	0.5	0	ρ	Normal	Vibrated	-
	LNC8	monotonic		56.5	ρ	Normal	Vibrated	1- Ø 6 mm
	HNC7	monotonic		0	ρ	High	Vibrated	-
	HNC8	monotonic		56.5	ρ	High	Vibrated	1- Ø 6 mm

- LNC = Normal strength vibrated concrete
- LSCC= Normal strength self- compacting concrete
- HNC= High strength vibrated concrete
- HSCC= High strength self-compacting concrete

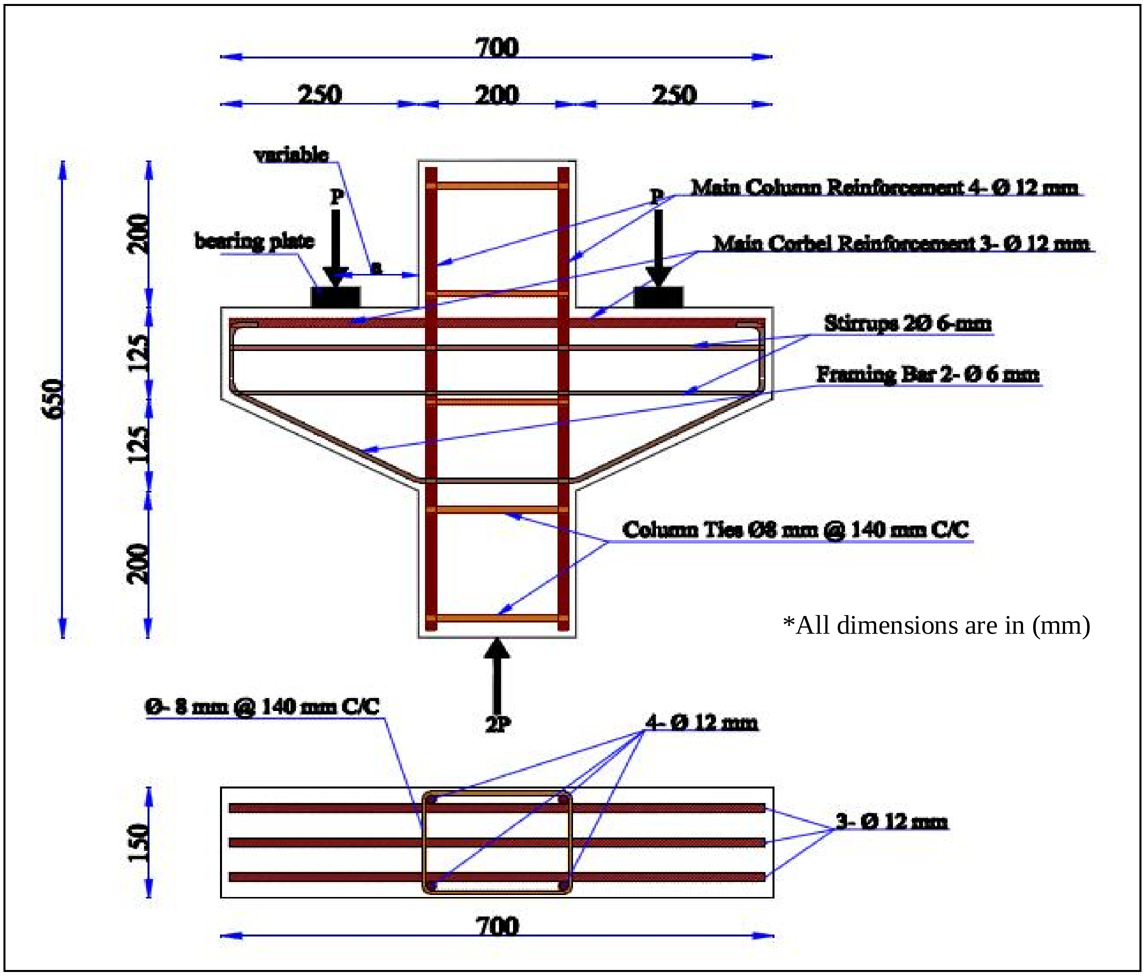


Figure 1 Details of tested corbel.

2.1 Material Properties

Standard tests according to the American Society for Testing and Materials (ASTM) and Iraqi Standard Specification were carried out to determine the properties of used materials.

Ordinary Portland cement produced at Northern Cement Factory (Tasluja-Bazian) was used throughout this study. Test results comply with the requirements of the Iraqi Standard Specification I.Q.S. No.5, (1984) [8].

Natural sand brought from AL- Kharbite region (in the west of Iraq) was used to produce the required concrete mixes for this study. The fine aggregate had (4.75mm) maximum size with rounded partial shape and smooth texture with fineness modulus of (2.36). The obtained results indicate that, the fine aggregate grading is within the limits of the Iraqi Specification No.45,(1984) [9] and ASTM C33- 03 [10].

Crushed gravel of maximum size of (10 mm) brought from Al-Niba'ee region was used. The grading of this aggregate type and its physical properties, conforms to the Iraqi specification No.45,(1984) [9] and ASTM C33- 03[10].

Deformed steel bars of (12 mm) diameter were used as the main tension reinforcement for corbels and as longitudinal reinforcement for the supporting column. Deformed steel bars of (φ 8 mm) diameters were used as tie bars for the column. Smooth plain bars of (φ 6 mm) diameter were used as shear reinforcement and framing bars of the tested corbels. Three specimens for each bar size were tested according to ASTM A 6115M- 02[11]. Properties of the reinforcing bars are presented in Table 2.

Table 2 Properties of the reinforcing bars*.

Nominal diameter (mm)	Measured diameter (mm)	Surface texture	Area (mm^2)	f_y (MPa)	**F_u (MPa)	Employment
6	6.1	plain	29.3	510	680	Shear reinforcement and framing bar for corbel
8	7.9	deformed	49.01	428	537	Column ties
12	12.7	deformed	126.7	532	715	Main reinforcement for corbel and longitudinal reinforcement for column

*****Steel bars were tested by using universal testing machine in Al-Nahrain University.

******Assume modules of elasticity (E) = 200×10^3 MPa

Limestone powder has been used as filler for concrete production for many years. It was used in this investigation to produce self-compacting concrete. The particle size of the limestone powder, according to EFNARC (2005) [12] ,must be less than (0.125 mm) to be most beneficial.

In the present work, the superplasticizer (S.P.) used is commercially known as "GLENIUM 51" and brought from O-BASF Construction Chemicals. It is a new generation of modified polycarboxylic ether. Also, it is free from chlorides and complies with ASTM C494-05 [13] types A and F. It is compatible with all Portland cements that meet recognized international standards.

2.2 .Mix Design

Different mixes have been used depending on the type and strength of concrete. Mixes proportion by weight were used throughout the present study to obtain two types of concrete (vibrated and self-compacting concrete), also to get two types of strength of concrete (high strength with average of (28 days) cylinder compressive strength of approximately (46 MPa), and normal strength with average of (28 days) cylindrical compressive strength of approximately (35 MPa) as shown in Table 3.

Table 3 Mix properties.

Mix no.	Mix description	Cement content (kg/m^3)	Sand content (kg/m^3)	Gravel content (kg/m^3)	Water (Liter)	S.P. (Liter)	Lime content (kg/m^3)	fc' MPa (28 days)
1	Vibrated concrete normal strength	420	650	1000	200	-	-	35
2	Vibrated concrete high strength	500	800	900	190	2.5	-	46
3	SCC normal strength	400	797	767	185	7.5	170	36
4	SCC high strength	550	855	767	165	20	50	48

Table 4 summarizes the results of mechanical properties of vibrated and SCC which has been obtained for different mixes at age of 28 days. Different types of concrete were used to give the main differences between vibrated and SCC, having high and normal strength. The obtained properties were the compressive strength (f_c'), splitting tensile strength (f_{ct}), modulus of rupture (f_r) and modules of elasticity (E_c). Each value presented in Table 4 represents the average value of two specimens.

Table 4 Mechanical properties of hardened concrete.

Mix designation	f_c' (MPa)	f_{ct} (MPa)	f_r (MPa)	E_c (MPa)
LNC	36.05	3.85	5.786	24650
LSCC	37.53	3.74	6.169	25130
HNC	46.50	4.20	8.285	29450
HSCC	48.04	4.73	8.345	30610

3. Testing Procedure and Test Results

The corbels were tested in an inverted position, as shown in Plate 1. The vertical load was applied to the top end of the column using a self-supporting loading frame of universal hydraulic testing machine of (3000 kN) capacity. The corbels were seated on steel supports with (150×60×50) mm bearing plates in a direct contact with horizontal surface of the corbel.

Plate 1 Corbel specimen Setup

Before loading was started, the dial gauges (to measure the deflection at each increment of loading, LVDTs wires) were placed in position to measure the strain at surface of concrete. Also, all steel reinforcement strain gauges are placed in their position before casting. The position of the applied load on the corbels at left and right sides of the face of the column (shear span (a)) was varied. Only vertical load was applied to the specimens. The load was increased using equal constant increments of 10 kN (one ton). At each load stage the deflection was recorded using electronic central dial gauge of (0.001 mm) accuracy.

3.1 Behavior of Tested Specimens

All tested corbels were free from cracks at early stages of loading, and behaved in an elastic manner at low load levels. The deflections were proportional to the applied loads. Consequently the stresses were small and the full cross section was active in carrying the applied loads. With load increments, more diagonal cracks were developed near the supports. It was observed that the first shear crack developed at regions close to the bearing plate. It was also found that the first crack was initiated at the corner, and while the crack was propagating along the column- corbel interface, the second crack formed at the inner edge of the bearing plate. The second crack was propagated much faster than the first crack. The first crack continued to propagate along the column face, while the second crack progressed toward the junction of the column and the sloped face of the corbel. The second crack which now became the primary or major crack, eventually ran between the inner edges of the bearing plate and the column- corbel junction at the sloping face, and was generally responsible for the failure of the corbel. Table 5 shows the shear cracking loads, ultimate loads and modes of failure for different tested corbels.

Table 5 Shear cracking, ultimate loads and failure modes of tested corbels.

Group	Corbel designation	a/d	A_h (mm^2)	Variable considered	Shear cracking (kN)	Ultimate load (kN)	Mode of failure
A	LNC1	0.5	113	Control	33.75	186	Diagonal splitting
	LNC2			90%	31.25	165	Inclined shear
	LNC3			80%	28.75	166.5	Shear
	LNC4			60%	-	175	Diagonal splitting
B	LSCC1	0.5	113	Control	23.75	217.5	Inclined shear
	LSCC2			90%	36.25	211	Diagonal splitting
	LSCC3			80%	33.25	209.5	Diagonal splitting
	LSCC4			60%	-	214	Inclined shear
C	HNC1	0.5	113	Control	33.75	210	Shear
	HNC2			90%	33.75	181.25	Diagonal splitting
	HNC3			80%	32.5	181.25	Shear
	HNC4			60%	39	192.5	Diagonal splitting
D	HSCC1	0.5	113	Control	32.5	229	Inclined shear
	HSCC2			90%	53.75	215	Inclined shear
	HSCC3			80%	48	217.5	Diagonal splitting
	HSCC4			60%	41.25	221	Diagonal splitting
E	LNC5	0.7	113	a/d	26.25	175	Diagonal splitting
	LNC6	0.3		a/d	53.75	290	Shear
	HNC5	0.7	113	a/d	25.1	190	Inclined shear
	HNC6	0.3		a/d	64	410	Shear
F	LNC7	0.5	0	A_h	21.25	160	Diagonal splitting
	LNC8		56.5	A_h	26.25	192.5	Diagonal splitting
	HNC7		0	A_h	-	175	Inclined shear
	HNC8		56.5	A_h	30	208.5	Diagonal splitting

For specimen LNC1 which was tested under monotonic load, the first shear crack and ultimate loads were 33.75 kN and 186 kN respectively. The other three corbels of this group were tested under repeated loading with (90%, 80%, and 60%) of the ultimate load of reference corbel 186 kN. Five cycles were carried out on each tested corbel with constant increments controlling the testing machine increasing (during loading) and decreasing (during unloading). Steel reinforcement strain, average concrete strain and load- deflection values were recorded at each increment of loading.

From the results exhibited in Table 5, it is observed that the load carrying capacity of the corbel specimens of group A decreases by a percentage of (6% to 11.3%) as compared with the ultimate failure load of reference control specimen LNC1.

Plates 2 to 5 show the cracks pattern after testing corbels of group (A).

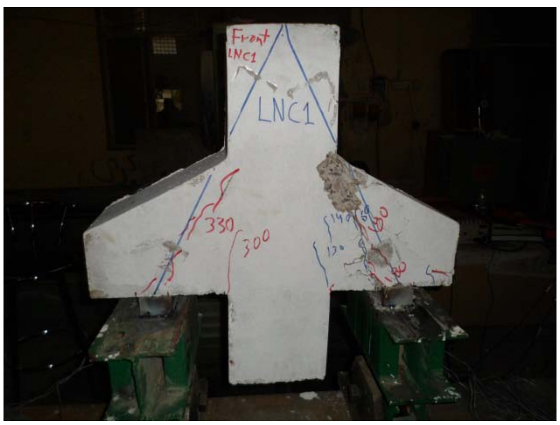


Plate 2 Crack pattern for corbel LNC1 (monotonic load) after testing

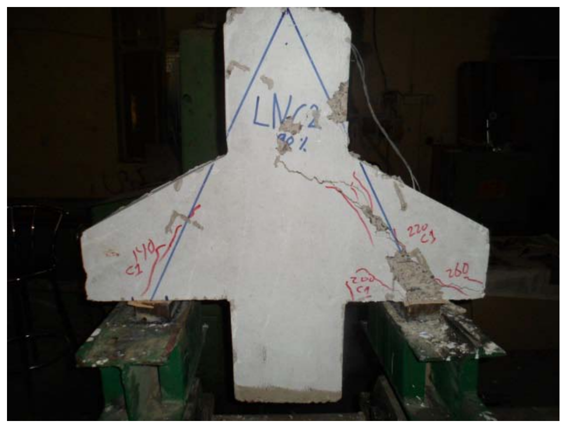


Plate 3 Crack pattern for corbel LNC2 (repeated load 90%) after testing

Plate 4 Crack pattern for corbel LNC3 (repeated load 80%) after testing

Plate (5) Crack pattern for corbel LNC4 (repeated load 60%) after testing

Referring to Table 5, one can observe that the load carrying capacity of SCC corbels (group B) under repeated loading decreases by a small percentage of (1.7% to 3.7%) as compared with the ultimate failure load of reference control specimen (LSCC1). It can be concluded that the use of SCC increases the load carrying capacity of corbels under repeated loading when compared with corbels of group A which were cast with vibrated concrete.

In group C, four corbels were cast with high strength vibrated concrete and tested with the same manner as that of groups A and B. Test results are shown in Table 5. The table reveals that the shear strength of the control corbel increases by 11.5% when compared with the same corbel as that of group A (both corbels were cast using vibrated concrete but they differ in their compressive strength). The corbels tested using repeated loading scheme show a decrease in the strength by (8.4%, 13.7% and 13.7%) of the ultimate failure load of control corbel after five cycles of repeated loading of (60%, 80% and 90%) respectively. The age of the corbels at testing time was 140 days.

Test results of high strength corbels with SCC are presented in Table 5. It is obvious from these results that only 6.2% reduction in the strength is obtained for the corbel tested under repeated loading of 90% of the ultimate load compared to control corbel after five cycles. The self compacting concrete affects also, the first shear cracking under repeated loading which makes corbels more durable. The compressive strength of concrete is increased proportionally with time for SCC.

3.2 Effect of the Considered Variables

Effect of repeated loading level, shear span to effective depth ratio (a/d), concrete compressive strength, horizontal stirrups and the use of SCC will be discussed in this section. The combination between these parameters according to test program is also considered.

3.2.1 Effect of Repeated Loading Level

Most of the previous work done had dealt only with reinforced concrete corbels subjected to loads monotonically increased to failure. In practice, there were many cases in which a structure can be subjected to high intensity of a repeated proportional loading or non-proportional type, such loading becomes significant in structures subjected to earthquake, hurricane or a large live load to dead load ratio [14,15,16].

The effect of repeated loading on the mode of failure, first cracking load and the reduction in the strength of the tested corbels is described in Table 6. The mode of failure was nearly the same with corbels subjected to monotonic loads. However, the number of cracks and their distribution were rather more different than corbels under monotonic loading. This produces a somewhat less brittle behavior for corbels under repeated loading. The reason may be due to the fact that specimens under repeated loading exhibit more deformations in main bars and deflections at the loading point. It can be noted that corbel LNC2 (90% of the ultimate load carried out by control corbel) failed during the third cycle, and corbel HSCC3 (80% of the ultimate load carried out by control corbel) was tested for seven cycles to obtain the differences from other specimens which were tested for five cycles and then up to failure. Corbel LNC2 failed because it reached the monotonic ultimate load and not because of the reduction in carrying capacity as a result of repeated loading effect. Careful observation of the specimens during testing indicates that when a corbel is loaded into the post yield range and then unloaded, residual tensile strain in the steel takes place at cracked regions and let the cracks remains open upon unloading.

The effect of repeated loading on the carrying capacity of corbels would be seen through comparing similar corbels both under monotonic and repeated loading. The maximum load carrying capacity of corbels subjected to repeated loading levels of (90%, 80%, and 60%) relative to similar corbels subjected to monotonic loading until failure is shown in Table 6. As can be seen the ratio (load capacity with repeated loading/ monotonic load capacity) has a range of (86.3% to 94%) for both (normal and high strength) vibrated concrete, while range of (93.8% to 98.3%) for both (normal and high strength) SCC is observed. It appears that this ratio increases when the SCC is used with other variables kept in the test program.

Table 6 Effect of repeated loading on tested corbels.

Group	Corbel designation	a /d	Variables considered	A_h (mm^2)	Mode of failure	1st shear cracking load(kN)	Ultimate load (kN)	Repeated load/static load ×100	No. of cycles
A	LNC1	0.5	Control	113	Diagonal splitting	33.75	186	100%	-
	LNC2		90%		Inclined shear	31.25	165	88.7%	3
	LNC3		80%		Shear	28.75	166.5	89.5%	5
	LNC4		60%		Diagonal splitting	-	175	94%	5
B	LSCC1	0.5	Control	113	Inclined shear	23.75	217.5	100%	-
	LSCC2		90%		Diagonal splitting	36.25	211	97%	5
	LSCC3		80%		Diagonal splitting	33.25	209.5	96.3%	5
	LSCC4		60%		Inclined shear	-	214	98.3%	5
C	HNC1	0.5	Control	113	Shear	33.75	210	100%	-
	HNC2		90%		Diagonal splitting	33.75	181.25	86.3%	5
	HNC3		80%		Shear	32.5	181.25	86.3%	5
	HNC4		60%		Diagonal splitting	39	192.5	91.6%	5
D	HSCC1	0.5	Control	113	Inclined shear	32.5	229	100%	-
	HSCC2		90%		Inclined shear	53.75	215	93.8%	5
	HSCC3		80%		Diagonal splitting	48	217.5	94.9%	7
	HSCC4		60%		Diagonal splitting	41.25	221	96.5%	5

3.2.2 Effect of Shear Span to Effective Depth Ratio

In general, when the shear span to effective depth (a/d) ratio is decreased an increase in the value of the cracking loads has been obtained for corbels having the same properties with other variables kept constant. For normal strength vibrated concrete corbels, when the (a/d) decreases from (0.5 to 0.3), an average increase in the cracking load of about 59.3% is obtained, while when the (a/d) decreases from (0.7 to 0.5), an average increase in the cracking load of about 28.5 % has been achieved. When the (a/d) ratio decreases from (0.7 to 0.3) the average increase in the cracking load was about 104.7 %. This effect is clearly shown in Figure 2

For high strength vibrated concrete corbels, as the shear span to effective depth ratio (a/d) decreases an increase in the value of the cracking load has been obtained for corbels having the same amounts of horizontal stirrups. When the (a/d) ratio decreases from (0.5 to 0.3) an average increase in the cracking load of 89.6 % has been obtained. While when the (a/d) ratio decreases from (0.7 to 0.5) an average increase in cracking load of 34.4 % is achieved. When the (a/d) ratio decreases from (0.7 to 0.3) the average increase in cracking load is noticed to be 155 %. This effect is clearly shown in Figure 3.

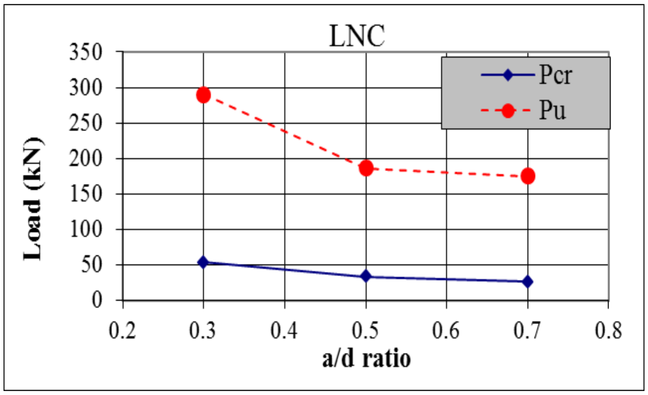


Figure 2 Effect of a/d ratio on cracking and ultimate loads for LNC corbels

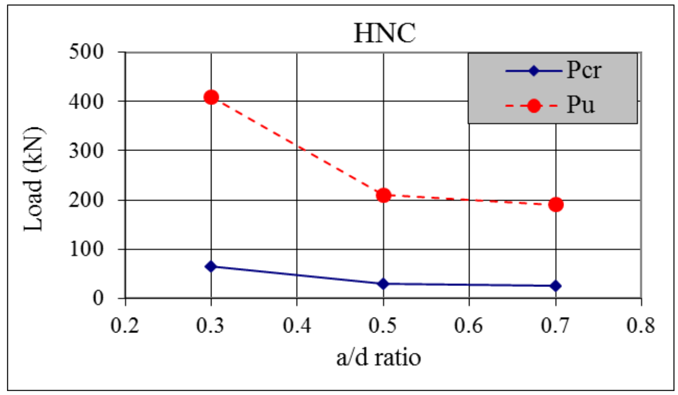


Figure 3 Effect of a/d ratio on cracking and ultimate load of HNC corbels

3.2.3 Effect of Horizontal Stirrups on Cracking and Ultimate Loads

In order to study the effect of the presence of secondary horizontal closed stirrups on the cracking load, different stirrups areas were considered. For the vibrated normal strength concrete corbels having the same (a/d) ratio, the increase in the amount of horizontal stirrups bars from zero to 56.5 mm^2 causes an increase in the cracking and ultimate loads of about 23.5% and 20.3% respectively. While the increase in the amount of horizontal stirrups (A_h) from 56.5 mm^2 to 113 mm^2 causes an increase in the cracking and ultimate loads of about 28.5 % and - 3.4 % respectively, which indicates an insignificant effect on the ultimate loads.

The effect of the presence of secondary horizontal closed stirrups on the cracking and ultimate loads of high strength vibrated concrete was studied using the same (a/d) ratio. It is found that the increase in the amount of horizontal stirrups bars from zero to 56.5 mm^2 causes an increase in the ultimate load of about 19.1 % (cracking load not recorded for corbel HNC7 when tested, so no comparison with others corbel cracking loads is given) and when the area of stirrups increases from 56.5 mm^2 to 113 mm^2 an increase in the cracking and ultimate loads of about

4.3% and 0.7% respectively is obtained, as shown in Figure 4, therefore, it can be concluded that the horizontal stirrups has insignificant effect on cracking and ultimate loads of corbels with high strength concrete.

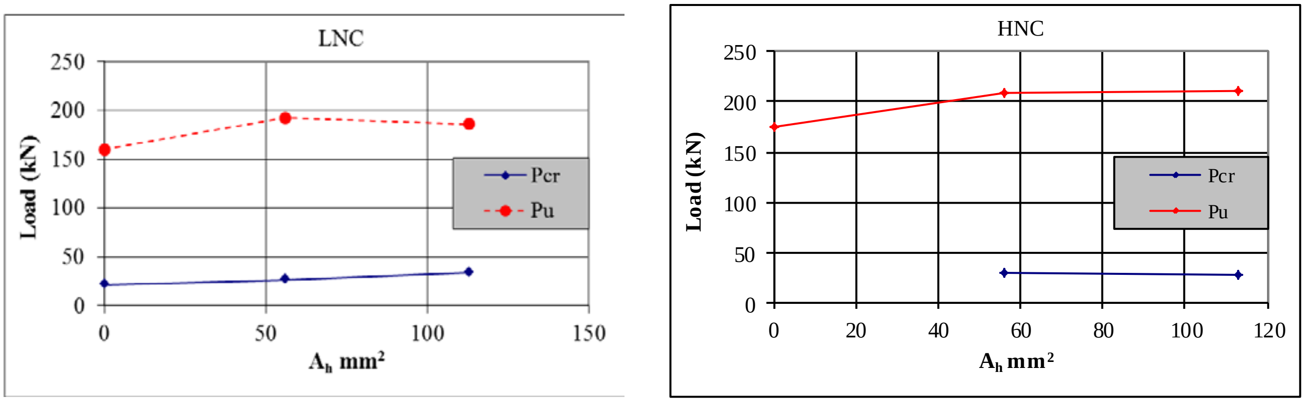
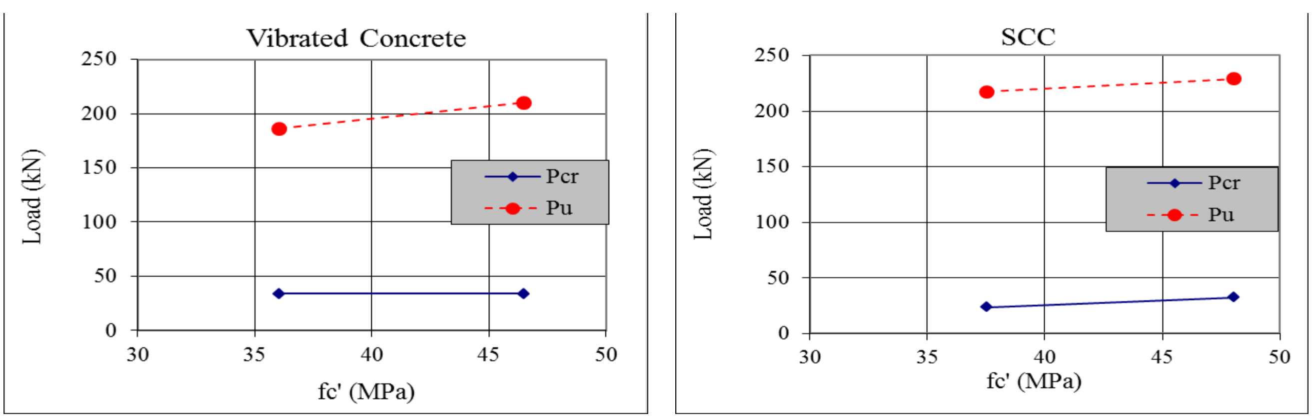


Figure 4 Effect of horizontal stirrups on the ultimate load of corbels with (a/d =0.5)

3.2.4 Effect of Concrete Compressive Strength

Effect of the parameter (f_c') on cracking and ultimate loads and the ratio between them for vibrated and SCC corbels tested in this study are shown in Figure 5. The effect is studied for different cases with the other parameters a/d, A_h, and repeated loading level are kept constants. Two types of compressive strength have been used: normal compressive strength for vibrated and SCC (f_c' ranges between 31 MPa and 37.5 MPa) and high compressive strength for vibrated and SCC (f_c' ranges between 42 MPa and 48 MPa).



(a) Comparison between LNC1 and HNC1corbels.

(b)Comparison between LSCC1 and HSCC1 corbels.

Figure 5 Effect of concrete compressive strength on corbels cracking and ultimate loads.

From the obtained results, it is obvious that the increase in (fc') leads to a significant increase in ultimate loads for all corbels. An insignificant effect on cracking loads was noticed, using the same (a/d, and A_h) for vibrated concrete tested under monotonic load. The improvements in the ultimate load due to increase in (fc') value ranges from 8.3% to 41.3%. This improvement is reduced when the (a/d) ratio increases, while it is approximately similar to the two considered values of A_h.

For corbels LNC5 and HNC5, the cracking load is reduced due to the increase in (fc') value as shown in Table 5 which represents an abnormal result due to experimental and observation circumstances.

From increasing compressive strength results, one can conclude that the improvement in the ultimate load is more significant than the improvement in the cracking load since the average increases is about 16% for the ultimate load and about 5.1% for the cracking load. For SCC corbels LSCC1 and HSCC1, the improvement in the cracking load is more significant than the improvement in the ultimate load since the increase is 36.8% for cracking load and 5.1% for ultimate load and these results depend on the age of tested corbels.

3.3 Load Deflection Relationship

Experimental load- deflection curves obtained for the tested corbels are shown in Figures 6 through 13 (Groups A and B). The deflection represents the movements of the loading jack (i.e. deflection at the central line joining the two corbels) of the corbel system. Each one of these curves is initiated in a linear form with constant slope. After cracking, the load deflection response takes a nonlinear form with a varying slope.

The shape of the various load- deflection curves at the post cracking stages of behavior and stages closed to the maximum load appear to depend on the type of applied load (monotonic or repeated load), shear span to effective depth ratio, and the cross sectional area of the horizontal closed stirrups.

For corbels tested under repeated loading in groups (A, B, C and D), the loading sequence was controlled by the deflections imposed on corbels (i.e. the location of the supports). The curve obtained under repeated loading is called “the hysteresis curve”. The hysteresis response effectively indicates the behavior of reinforced concrete corbels under cyclic loading. The area within the cycle of the load- deflection curve is critical parameters for cyclic response because it is a measure of the energy absorbed after sever cycling. This indicates the influence of cyclic loading on stiffness and strength degradation [15,16].The load versus deflection hysteresis loops for all tested twelve specimens show a degradation in load carrying capacity during repeated cycles that is characteristic of reinforced concrete due to cracking of the concrete and yielding of the reinforcing steel (main bars). The load- deflection curves show an important characteristic regarding the area enclosed by the hysteresis loop which decreases with increasing cycles at a constant ductility ratio [17].

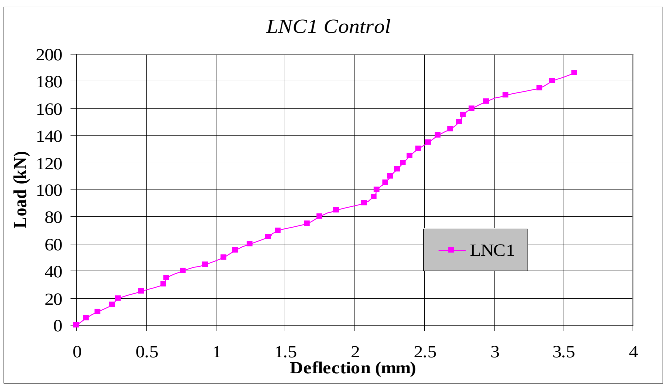


Figure 6 Load- deflection response for control corbel LNC1 (monotonic loading).

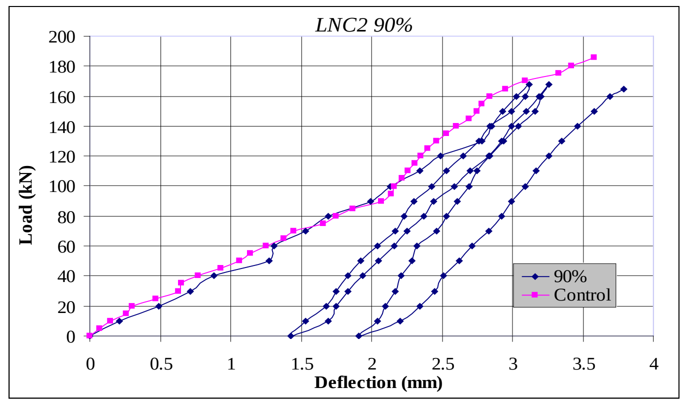


Figure 7 Load- deflection response for corbel LNC2 (90% loading level).

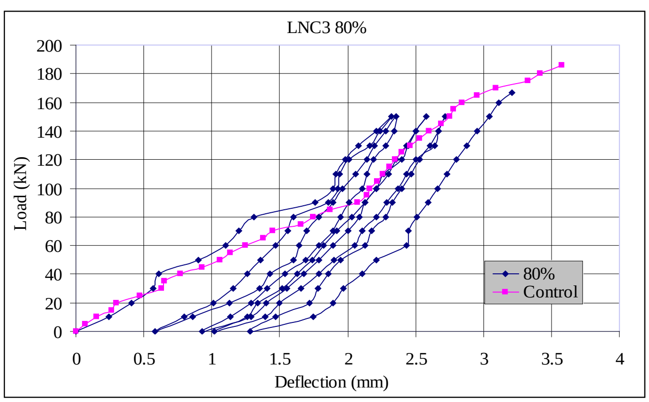


Figure 8 Load- deflection response for corbel LNC3 (80% loading level).

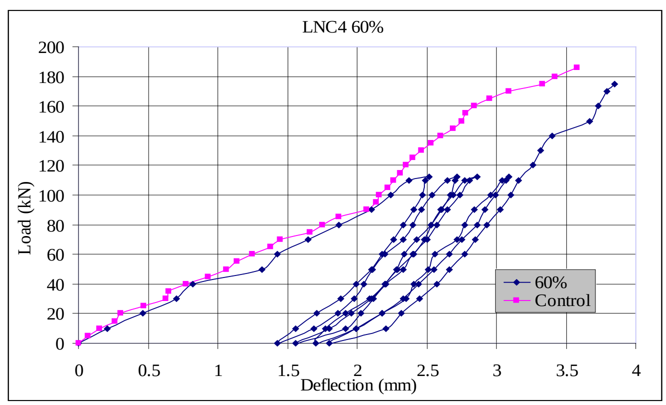


Figure 9 Load- deflection response for corbel LNC4 (60% loading level).

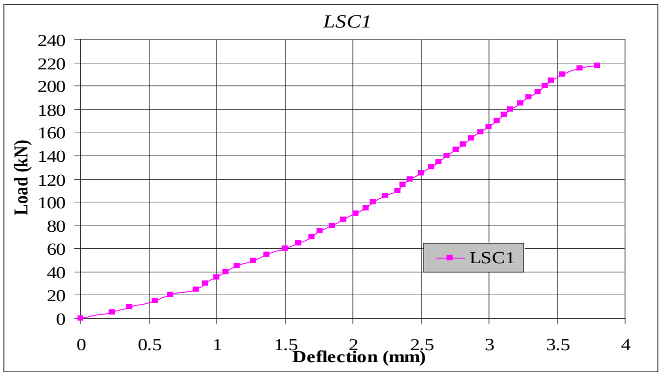


Figure 10 Load- deflection response for corbel LSCC1 (monotonic loading).

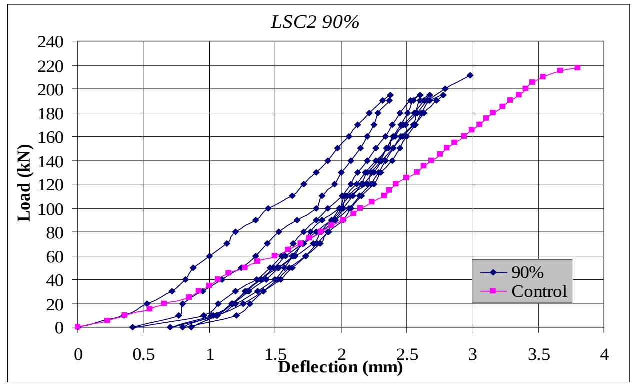


Figure 11 Load- deflection response for corbel LSCC2 (90% loading level).

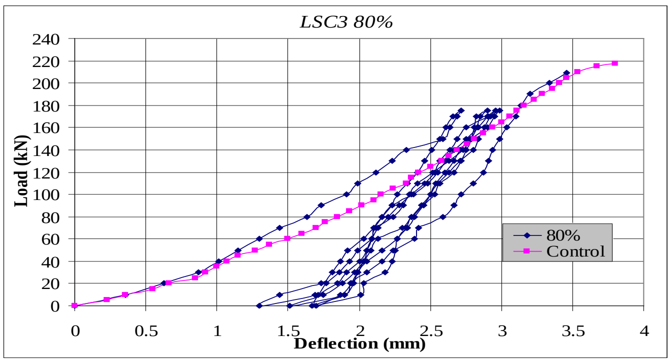


Figure 12 Load- deflection response for corbel LSCC3 (80% loading level).

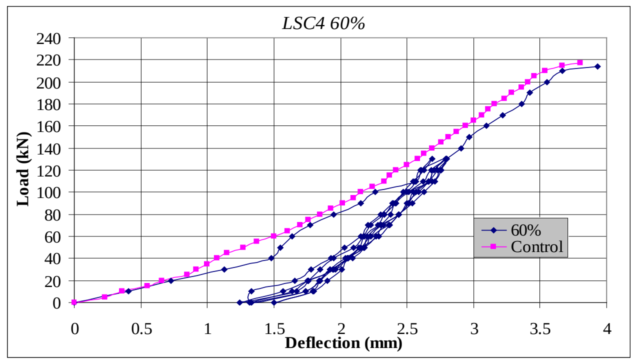


Figure 13 Load- deflection response for corbel LSCC4 (60% loading level).

6.Conclusions

1. The congested corbel reinforcement according to the requirements of ACI-318M- 11 Code provisions and the small size of corbels when compared with other structural elements make the use of SCC better solutions than the use of vibrated concrete.
2. The specimens cast with SCC and tested under repeated loading exhibit higher first cracking load than those cast with vibrated concrete for both normal and high compressive strengths of concrete.
3. Corbels reinforced with main bars only failed in brittle manner soon after reaching their ultimate loads.
4. The percentage of secondary reinforcement changes the mode of failure. As the percentage of stirrups is increased by 50%, the mode of failure changes to a more ductile one.

5. It was found that for all tested corbels the decrease in the shear span to effective depth ratio (a/d) from 0.5 to 0.3 increases the cracking load by about 59.3% for normal strength vibrated concrete corbels and 89.6% for high strength vibrated concrete corbels. While by decreasing the (a\d) ratio from 0.7 to 0.5 the increase in the cracking load is 28.5% and 34.4% for normal and high vibrated concrete compressive strength respectively. Also, when the (a\d) ratio decreases from 0.7 to 0.3, the increase in the cracking load is 104.7% and 154.9% for normal and high strength vibrated concrete respectively.
6. The decrease in the shear span to effective depth ratio (a\d) from 0.5 to 0.3 increases the ultimate load by 55.9% for normal strength vibrated concrete corbels and 95.2% for high strength vibrated concrete corbels. While by decreasing the (a\d) ratio from 0.7 to 0.5 the increase in the ultimate load is 6.2% and 10.5% for normal and high vibrated concrete compressive strength respectively. While, when the (a\d) ratio is decreased from 0.7 to 0.3, an increase in the ultimate load of about 65.7% and 115.7% is achieved for normal and high vibrated concrete strengths respectively.
7. For vibrated normal strength concrete corbels having the same (a/d) ratio, the increase in the amount of secondary reinforcement (horizontal stirrups bars) from zero to 56.5 mm^2 causes an increase in the cracking and ultimate loads of about 23.5% and 20.3% respectively. While the increase in the amount of horizontal stirrups from 56.5 mm^2 to 113 mm^2 causes an increase in the cracking load of about 28.5 %, and a decrease in ultimate loads of about 3.4 %, which indicates an insignificant effect of the horizontal stirrups on the ultimate loads.
8. The horizontal stirrups have an insignificant effect on cracking and ultimate loads of corbels with high strength concrete. It is found that for high strength vibrated concrete corbels having the same (a\d) ratio, the increase in the amount of horizontal stirrups bars from zero to 56.5 mm^2 causes an increase in the ultimate load of about 19.1 % (cracking load is not recorded for high strength vibrated corbel specimens with zero horizontal reinforcement ratio when tested, so no comparison with other corbel cracking loads is given). While, when the area of stirrups increases from 56.5 mm^2 to 113 mm^2 a decrease in the cracking and ultimate loads of about 4.3% and 0.7% , respectively is obtained.
9. The specimens subjected to repeated loading failed in a rather more ductile manner compared with those subjected to monotonic loading. In addition, it was found that

repeated loads increase the total deflection at failure when compared with specimens subjected to monotonic loading at failure.

10. Corbels subjected to repeated loading always experience some increase in the deflection in consecutive cycles. In addition, it was found that the consecutive increments of deflection with repeated loads were decreased.

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