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Experimental Study on the Behavior of Normal and High Strength Self-compacting Reinforced Concrete Corbels

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Abstract

The main purpose of this experimental study is to investigate the behavior and strength of self-compacting reinforced concrete corbels with and without steel fibers. The program included (10) specimens, in which the shear span to effective depth ratio (a/d), the amount of steel fiber (V_f), and compressive strength(f'c)of self-compacting concrete were varied. All specimens had the same length, thickness and main reinforcement and they were subjected to concentrated vertical loads only.

It was found that the addition of steel fibers delays the formation of the cracking of fibrous corbel relative to nonfibrous corbels and the cracking load and ultimate load for Normal strength self-compacting concrete(NSCC) corbels increase by 31.5% and 25.3% when the volume of steel fibers increases from 0% to 0.4%. While the cracking and ultimate loads increases by 7.3% and 3.1% when the volume of steel fibers increases from 0.4% to 0.8% and the increase in volume of steel fibers from 0% to 0.8% results in increasing the cracking load and ultimate load by about 41.1% and 29.1% respectively.

Keywords: corbels, reinforced concrete, self-compact, steel fibers, strength, compressive strength, shear, cracking load.

دراسة عملية لسلوك الكتائف الخرسانية المسلحة والمصنوعة من الخرسانة الذاتية الرص ذات المقاومة الاعتيادية والعالية

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الخلاصة :

يهدف البحث لدراسة سلوك ومقاومة الكتائف الخرسانية المسلحة ذاتية الرص والرص والمعززة بالالياف او بدونها ويتضمن برنامج البحث (10) نماذج ذات ابعاد وكمية حديد تسليح رئيسة ثابتة ،والمتغيرات التي تم تناولها في البحث نسبة فضاء القص الى العمق الفعال (0,3 ، 0,45 ، 0,6) ونسبة الالياف الحديدية (0 ، 0,4 ، 0,8) % ومقاومة الانضغاط.

لقد وجد من خلال البحث ان اضافة الالياف الحديدية يؤخر تكون حمل التشقق في الكتائف الخرسانية المسلحة ، كما وجد ان حمل التشقق والحمل الاقصى يزداد بنسبة (31,5 ، 23,3) % عندما تزداد نسبة الالياف الحديدية من (0 الى 0,4) % ، وان زيادة نسبة الالياف الحديدية من (0,4 الى 0,8) % يؤدي الى زيادة حمل التشقق والحمل الاقصى بنسبة (7,3 ، 3,1) % ، كما ان زيادة نسبة الالياف الحديدية من (0 الى 0,8) % تؤدي الى زيادة حمل التشقق والحمل الاقصى بنسبة (41,1 ، 29,1) % على التوالي.

1. Introduction

Corbels (or brackets) are very important structural members for supporting precast beams, gentry girders and bridges, which are usually built monolithically with columns (or walls) to support heavy concentrated loads, [1] **Figure (1).** Reinforced concrete corbels have become a common feature in building construction with the increasing use of precast reinforced concrete elements for the construction of buildings and bridges [2].

Because of the prevalence of precast concrete, the design of corbels has become increasingly important. The term “corbel” is generally restricted to cantilevers having shear span-depth ratios less than unity. Such a small ratio causes the strength of corbels to often be controlled by shear. Corbels are designed mainly to resist the vertical reaction Vu at the end of the supported beam, and sometimes they must also resist a horizontal force (Nuc) transmitted from the supported beam due to restrained shrinkage, creep, or temperature change, Figure (2). Typically, reinforcement for the corbel consists of primary tension steel, horizontal hoops and framing bars. [3], [4], [5]

Brackets and corbels tend to act as simple trusses or deep beams, rather than flexural members [5]**,** therefore, it was widely assumed that reinforced concrete corbels are principally shear transfer members. Conventional design procedures provide horizontal stirrups throughout the corbel depth as shown in **Figure (2),** to improve their shear capacities and reduce the likelihood of sudden failure. The design of reinforced concrete corbels has continuously been changing in recent years. The changes relate mainly to stirrup design and contribution to corbel strength. However, sometimes it can be difficult to comply with ACI Building Code requirements of cover and amount of shear reinforcement, due to the complexity of detailing and congestion of reinforcement, also this congestion could lead to difficulties in achieving fully compacted concrete, and result in poorer bond between reinforcement and concrete. One solution to this problem is to replace the conventional secondary reinforcement, i.e., stirrups with steel fibers. [6] (or use self-compact concrete)

The addition of various types of fibers to concrete leads to improvements in apparent bond between steel and concrete, the compressive strength, tensile strength, flexural strength, impact resistance, fracture toughness, fatigue resistance, crack control characteristic and ductility of the concrete. [2],[7], [8], [9]

The corbel shown in **Figure (3)** may fail by shearing along the interface between the column and the corbel, by yielding of the tension tie, by crushing or splitting of the compression strut, or by localized bearing or shearing failure under the loading plate.[5]

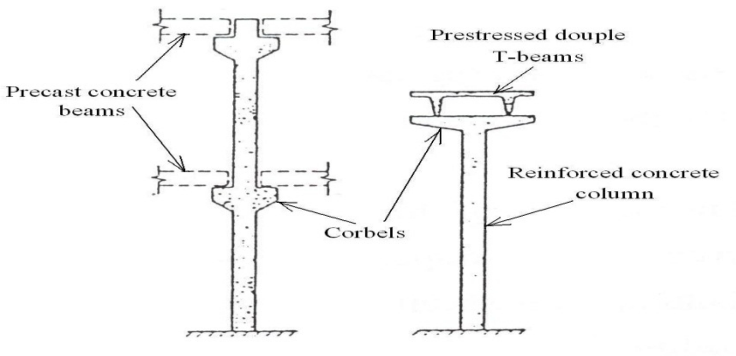


Fig .(1) Precast concrete column and corbels. [2]

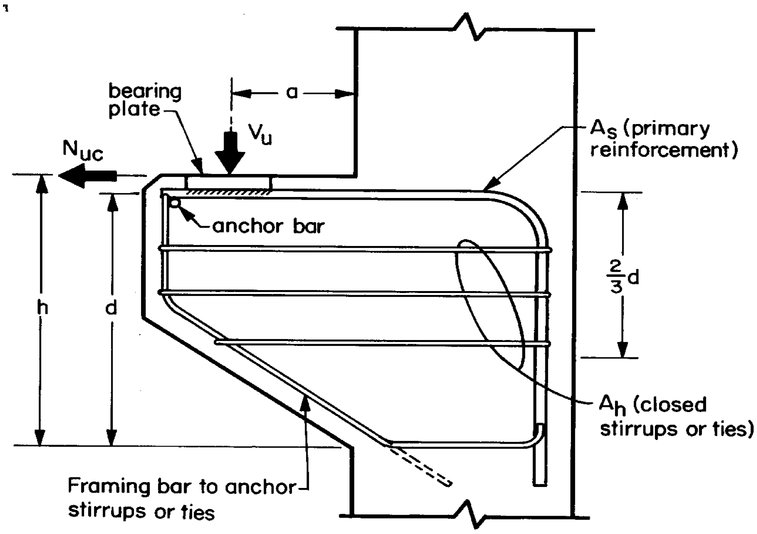


Fig .(2) Typical reinforced concrete corbel. [4]

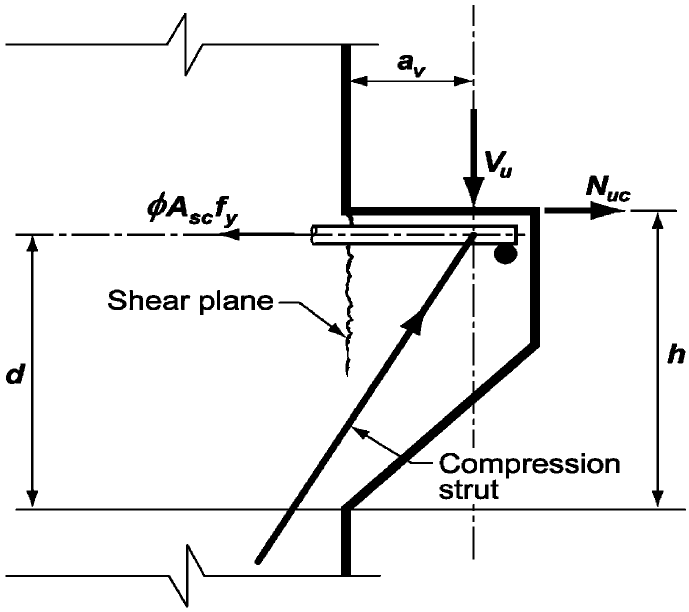


Fig .(3) Structural action of a corbel.[4]

2. Corbel details

The corbel and column dimensions as well as the column and corbel reinforcement were kept constant throughout the investigation **Figures (4a) and (4c)** shows the details of the specimens. Column dimensions and reinforcements ensure that their behavior would exclude column failure. The dimensions of the column supporting the two corbels on opposite side of the column were (150 x 200 x 650) mm, and were reinforced with four (10 mm) diameter longitudinal deformed bars at the corners and (8)mm diameter closed ties spaced at (150)mm center to center.

Corbels were reinforced with (12)mm diameter deformed steel bars, on tension side (as main reinforced) ,(10)mm diameter cross bars, which were welded to main bars close to the free end of each corbel to avoid bond failure [4], **Figure (4b)**

Fig .(4a)

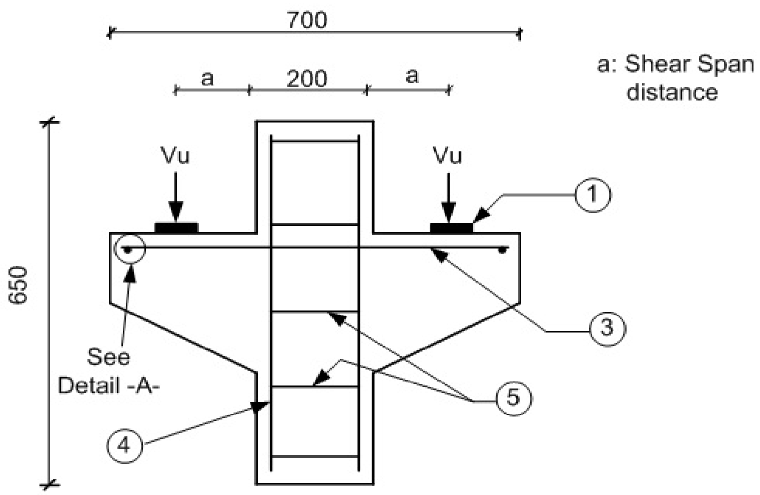
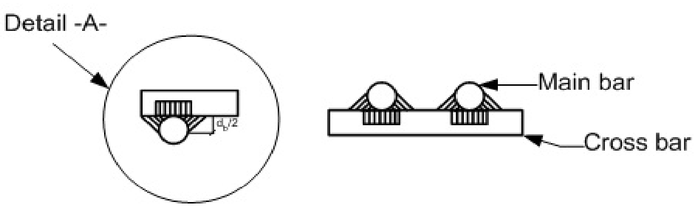
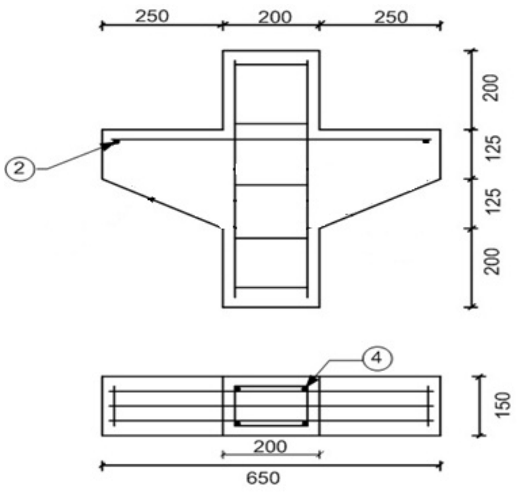


Fig .(4b)





1: Bearing plate
2: f 10 mm-cross bar welded to main bar.
3: 3 f 12 mm main reinforcement bars.
4: 4 f 10 mm column reinforcement
5: f 8 mm ties at 150 c/c

Fig .(4c)

Fig .(4) Details of a typical corbel, reinforcement and Details of welded bars

Table (1) Details of tested corbels and their parameters.

Corbel name	Type of Concrete	*f'c* MPa	a/d Ratio	Fiber content(V_f) %
C1	Nscc	33.75	0.3	-
C2	Nscc	33.75	0.45	-
C3	Nscc	33.75	0.6	-
C4	Nscc	34.75	0.45	0.4
C5	Nscc	35.34	0.45	0.8
C13	Hscc	65.31	0.3	-
C14	Hscc	65.31	0.45	-
C15	Hscc	65.31	0.6	-
C16	Hscc	67.27	0.45	0.4
C17	Hscc	67.71	0.45	0.8

3. Material properties

3.1 Cement

Ordinary Portland cement produced at Northern Cement Factory (Tasluja-Bazian) was used throughout this investigation, with the requirements of the Iraqi Standard Specification I.Q.S. No.5, 1984[10]

3.2 Fine aggregate

Natural sand brought from AL-Ukaidher region was used in concrete mixes for his investigation. The fine aggregate had (4.75mm) maximum size with rounded partial shape and smooth texture with fineness modulus of (2.78). The obtained results indicate that, the fine aggregate grading is within the Iraqi Specification No. 45/1984[11] as shown in **Figure (5).**

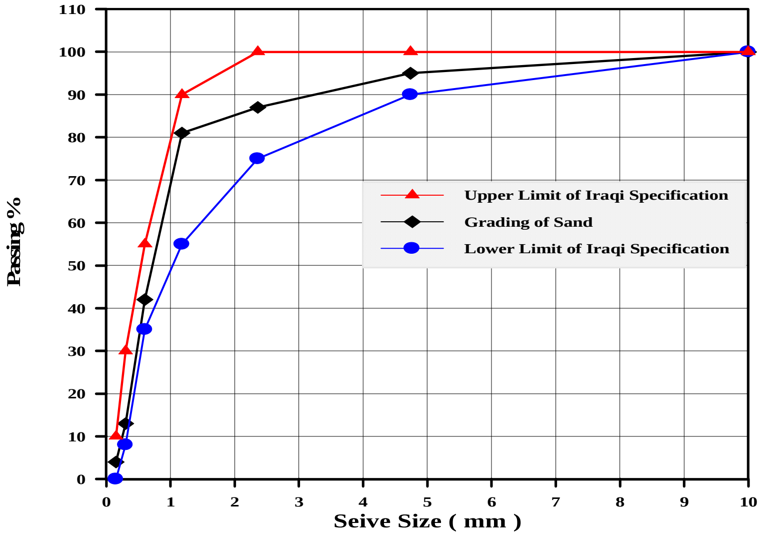


Fig .(5) Grading curve for fine aggregate with grading limits.[11]

3.3 Coarse aggregate

Crushed gravel of maximum size 10 mm brought from Al-Niba'ee region was used. **Figure (6)** show the grading of this aggregate, which conforms to the Iraqi Specification No.45/1984.[11]

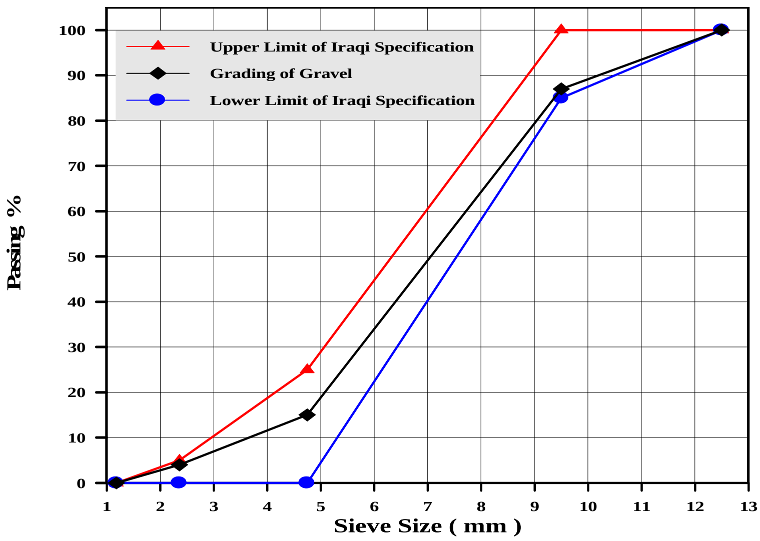


Fig .(6) Grading curve for coarse aggregate.[11]

3.4 Water

Ordinary tap water was used for both mixing and curing of all concrete specimens used in this investigation. It was free from injurious substances like oil and organic materials.

3.5 Steel fibers

High tensile steel fibers crimped type was used with different volume fractions of (0, 0.4 and 0.8%). **Table (2)** shows the properties of the used steel fibers.

Table .(2) Properties of steel fibers

Property	Specifications
Density	7860 kg/m^3
Ultimate strength	2000 MPa
Modulus of Elasticity	$200x10^3$MPa
Strain at proportion limit	5650 $x10^{-6}$
Poisson's ratio	0.28
Average length	30 mm
Nominal diameter	0.375 mm
Aspect ratio (L_f/D_f)	80

*From Manufacturer Catalogue

3.6 Superplasticizer

A superplasticizer type sulphonted melamine and naphthalene formaldehyde condensates, which are known commercially as Gleniume-51, was used in this work.

3.7 Limestone powder (LSP)

This material is locally named “Al-Gubra”. It is a white grinding material from lime-stones excavated from Al-Mosul province in the north of Iraq, Particle size of the limestone powder is less than 0.125 mm, it is confirm to EFNARC 2005[12]

4. Test results of self-compacting reinforced concrete corbels

Test results of self-compacting reinforced concrete corbels are shown in the **Table (3).** The first cracking load (Vcr) and the ultimate load (Vu) for each specimen is listed as well as the main variables studied in this research and their effects on the behavior of self-compacting reinforced concrete corbels.

Table .(3) Experimental crack and ultimate loads of reinforced concrete corbels

Corbel name	Type of Concrete	a/d Ratio	f'_c MPa	V_f %	V_{cr} kN	V_u kN	V_{cr}/ V_u %	Mode of failure
C1	Nscc	0.3	33.75	-	67	435	15.4	DS*
C2	Nscc	0.45	33.75	-	63	395	15.9	DS
C3	Nscc	0.6	33.75	-	57.5	338.5	16.9	DS
C4	Nscc	0.45	34.75	0.4	81.5	495	16.4	DS
C5	Nscc	0.45	35.34	0.8	87.5	510	17.1	DS
C13	Hscc	0.3	65.31	-	98	745	13.1	DS
C14	Hscc	0.45	65.31	-	81	600	13.5	DS
C15	Hscc	0.6	65.31	-	74.5	555	13.4	DS
C16	Hscc	0.45	67.27	0.4	107.5	761.5	14.1	DS
C17	Hscc	0.45	67.71	0.8	117	816.5	14.3	DS

DS* (Diagonal Splitting)

5. Behavior of self-compacting reinforced concrete corbels

In all tested corbels, at the early stages of loading reinforced concrete, corbels are free from any cracks and the amount of displacement is very small, because the stresses resulting from the applied loads are small at this stage of loading, and with the increase in the applied load values the cracks begin to appear.

The first cracks form when flexural cracks started at or near the junction of the tension face of the corbel and the face of column and continued to propagate slowly along column face or inside corbel before it stops during the development of the second major crack as shown **Figure (7).**

The second crack formed at the inner edge of the bearing plate and ran between the inner edge of the bearing plate and the column-corbel junction at the sloping face. This crack becomes the main or primary crack, which is generally responsible to for governing the mode of the failure in the corbel at the proceeding stage of loading as shown **Figure (7).**

Also, it was observed that the sets of shear cracks were developed near the supports, followed by a long shear crack at either one or both ends of supports for the double corbel system and extended toward the load point. Almost, main shear cracks occurred in corbels aligned parallel to the line drawn from the point of load application at the bottom face and the point of intersection of the corbel and the column at the top face.

When the applied load increases, the existing vertical flexural cracks and the inclined shear cracks propagate slowly accompanied by the formation of new cracks parallel to the inclined initial cracks located between column interface and the point of load application (shear span). Further increase in the applied load causes the inclined shear cracks to propagate until failure occurs. The failure is defined as the load level at which the load could no longer be increased, also some minor secondary cracks formed before failure took place.

Fig . (7) Crack patterns after testing self-compacting double system reinforced concrete corbels

6. Load deflection response of self-compacting reinforced concrete corbels:

The deflections were measured at the center of column using a digital gage of (0.01mm) accuracy as shown in **Figure (8).** The deflection represents the movement of the loading jack, i.e. average deflection of the two corbels (of each specimen) at the supports.Load deflection curves for self-compacting reinforced concrete corbels are shown in **Figure (9)** through **Figure (13).**

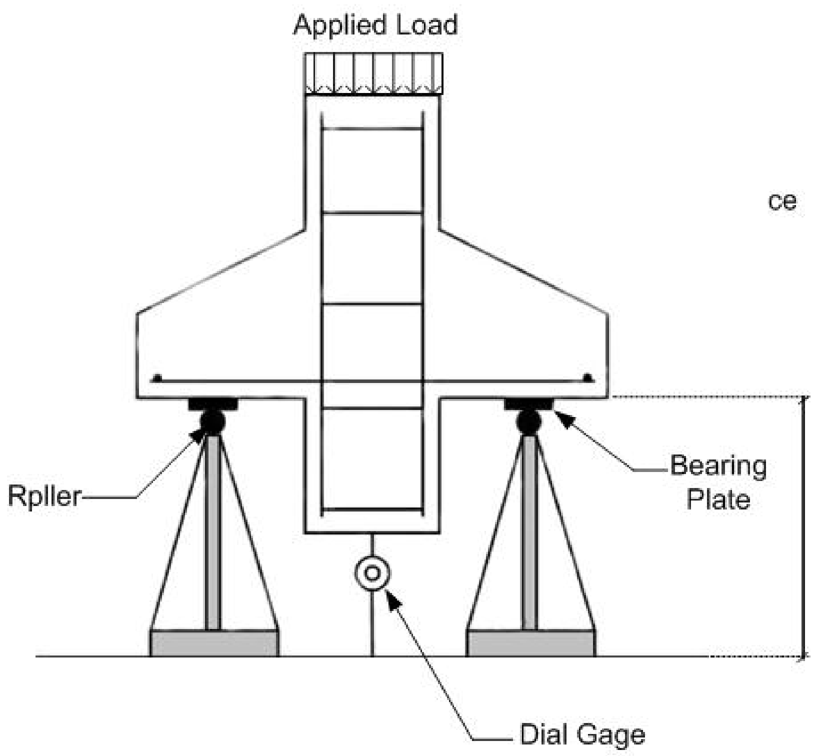


Fig .(8) Loading arrangement with measurement instrumentations on corbels.

6.1 Effect of shear span to effective depth ratio on load deflection response.

Figures (9) and **(11)**show that the increase in the shear span ratio (a/d) for NSCC corbels C1, C2 and C3 and HSCC corbels C13, C14 and C15 from 0.3 to 0.45 and from 0.45 to 0.6 leads to increase in the deflection values. The increase in a/d ratio increases bending moment, which causes an increase in the deflection value of corbel. At a specified load level of 100 kN, the deflection values of corbels C1, C2 and C3 are 1.1 mm, 1.25 mm, and 1.52 mm respectively. While, for HSCC the deflection values of corbels C13, C14, and C15 at the same load level are 0.96 mm, 1.09 mm, and 1.37 mm respectively.

It is clear that the deflection for NSCC corbels is greater than that of HSCC corbels for the same load level of all shear span to the effective depth ratios because the stiffness of HSCC corbels is greater than that of NSCC corbels.

6.2 Effect of steel fiber content on load deflection curve.

The increase in the volume of fraction of steel fibers with a constant shear span to effective depth ratio (a/d=0.45), and all other variables, leads to decrease the deflection values. It was found that at specified load level of 100 kN the deflection values of the NSCC corbels C2 (V_f=0), C4 (V_f=0.4%) and C5 (V_f=0.8%) are 1.25 mm, 1.02 mm and 0.92 respectively. The deflection values of HSCC corbels C14 (V_f=0),C16 (V_f=0.4%) and C17

(V_f=0.8%) at the same load level (100 kN) are 1.09 mm, 0.96 mm and 0.86 mm respectively as shown in **Figures (10) and (12).**

It can be concluded that the presence of steel fibers results in delaying the initiate and expansion of cracks as well as resulting in enhancing the resistance of concrete to cracking. In the other hand the deflection decrease with increasing the amount of steel fibers, and the increasing compressive strength of concrete.

6.3 Effect of compressive strength on load deflection response:

From **Figure (13),** it is clear that the increase in compressive strength (*f'c*) value decreases the deflection values. The reduction in deflection is observed at all load levels because the increase in *f'c* leads to a significant improvement in the flexural rigidity (*EI*) which reduces the deflection for the same load level. Therefore, the deflection values of HSCC corbels are less than the deflection values of NSCC corbels for all stages of loading.

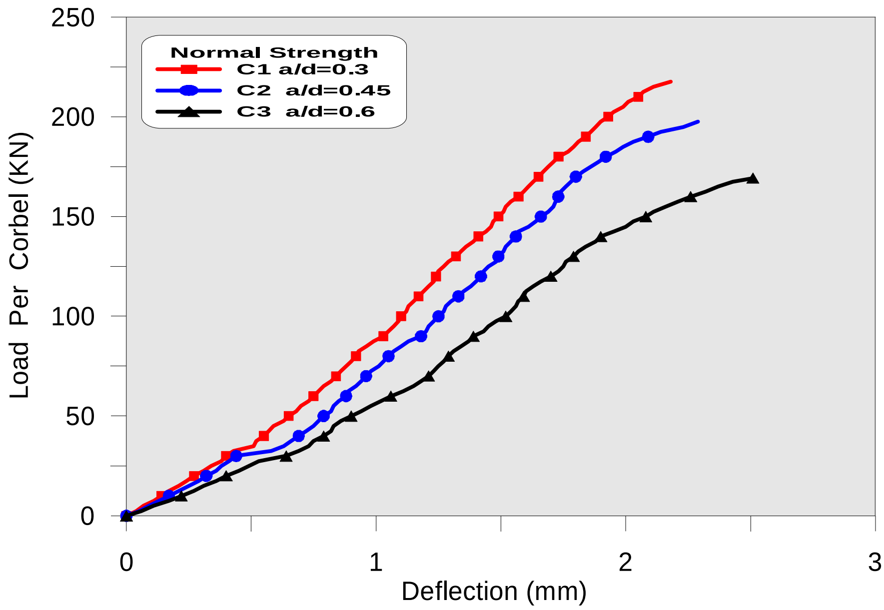


Fig .(9) Load deflection relationship of NSCC corbels for different values of shear span to effective depth ratio (a/d)

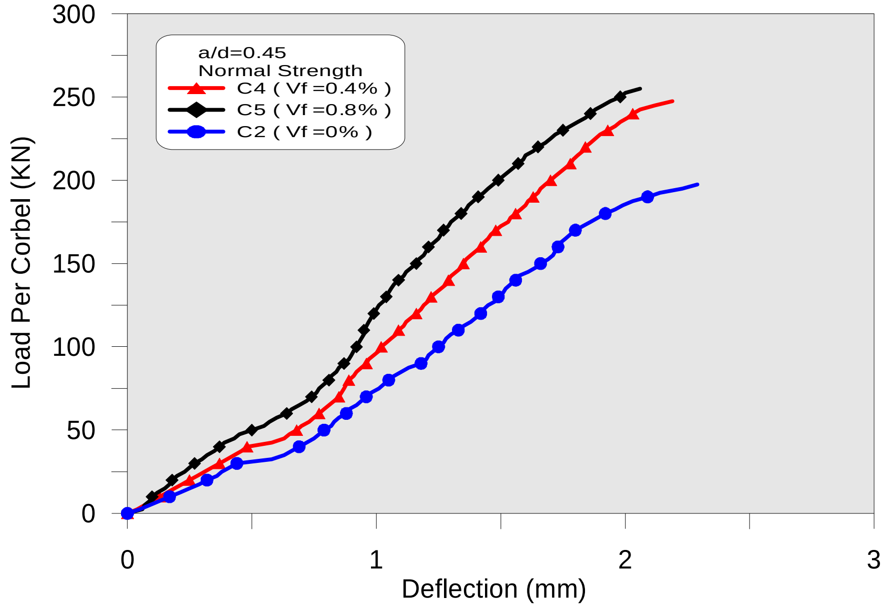


Fig .(10) Load deflection relationship of Nscc corbels for different volume of fraction of fibers (vf)

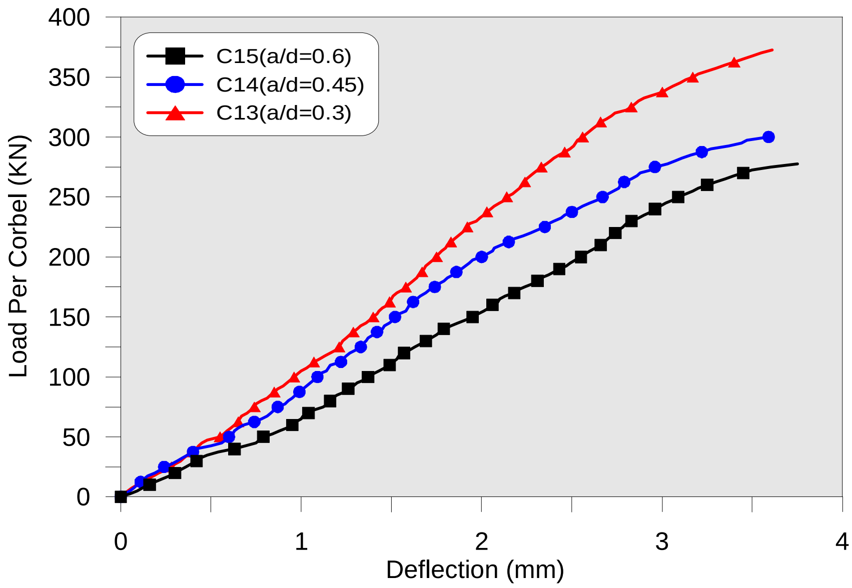


Fig .(11) Load deflection relationship of HSCC corbels for different values of shear span ratio (a/d)

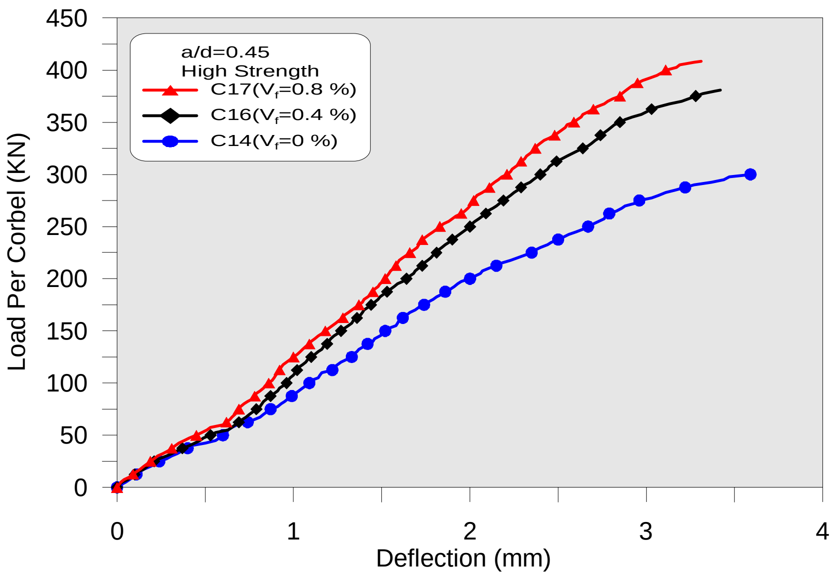


Fig .(12) Load deflection relationship of HSCC corbels for different volume fractions of fibers (Vf)

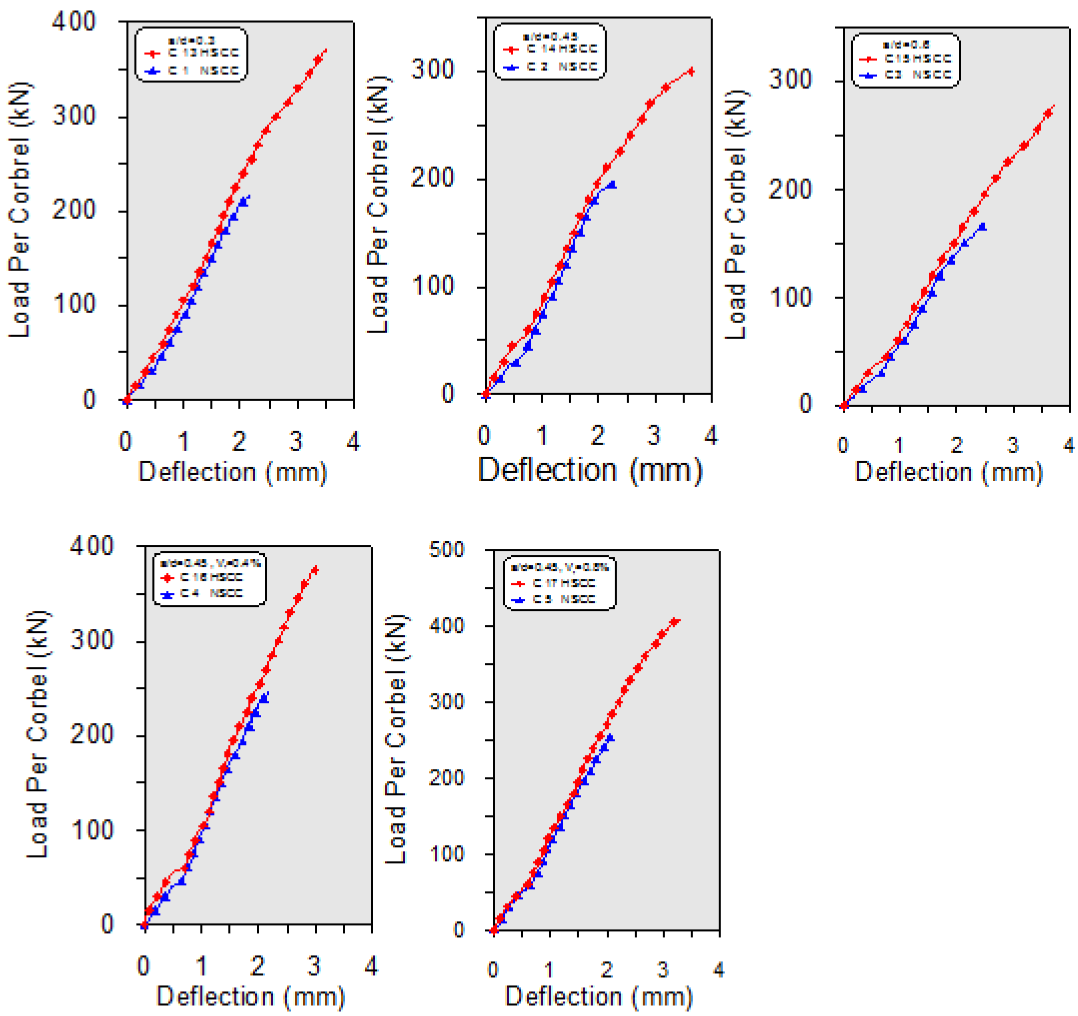


Fig .(13) Load deflection relationship of NSCC and HSCC corbels for the different considered variables

7. Cracking load and ultimate load capacity of self-compacting reinforced concrete corbels:

This sub-section, discusses the effect of the shear span to effective depth ratio(a/d), the volume of fraction of steel fibers (V_f), and strength of concrete (NSCC, HSCC) on the cracking and ultimate shear capacity of self-compacting reinforced concrete corbels.

7.1 Effect of shear span to effective depth ratio on cracking load and ultimate shear capacity

In general, as the shear span to effective depth ratio (a/d) decreases, an increase in the value of the cracking load is obtained for corbels having the same value of main reinforcement, horizontal reinforcement, strength of concrete and type of concrete. It was found that for NSCC corbels, when the (a/d) ratio decreases from 0.6 to 0.45, an increase in cracking load and ultimate load of about 7.8% and 16.7 % is obtained. While when the (a/d) ratio decreases from 0.45 to 0.3, an increase in the cracking load and ultimate load of about 8.1% and 10.1% is achieved. Also, when the (a/d) ratio decreases from 0.6 to 0.3 an increase in the cracking load and ultimate load of about 16.5% and 28.5% is obtained.

For HSCC corbels, as the (a/d) ratio decreases from 0.6 to 0.45, an increase in cracking load and ultimate load of about 8.7% and 8.1% is obtained. While when the (a/d) ratio decreases from 0.45 to 0.3, an increase in the cracking load and ultimate load of about 20.9% and 24.2% is achieved. Also, when (a/d) ratio decreases from 0.6 to 0.3 the increase in the cracking load and ultimate load of about 31.5% and 34.2% is obtained. This effect is clearly shown from the results listed below in **Table (4)** and **Figures (14)** and **(15).**

Table .(4) Effect of shear span to effective depth ratio on cracking and ultimate loads for NSCC and HSCC corbels

Concrete type		The decrease in the value of (a/d) ratio		
		% increase in Load		
		0.6 to 0.45	0.45 to 0.3	0.6 to 0.3
NSCC	Vcr	7.8	8.1	16.5
	Vu	16.7	10.1	28.5
HSCC	Vcr	8.7	20.9	31.5
	Vu	8.1	24.2	34.2

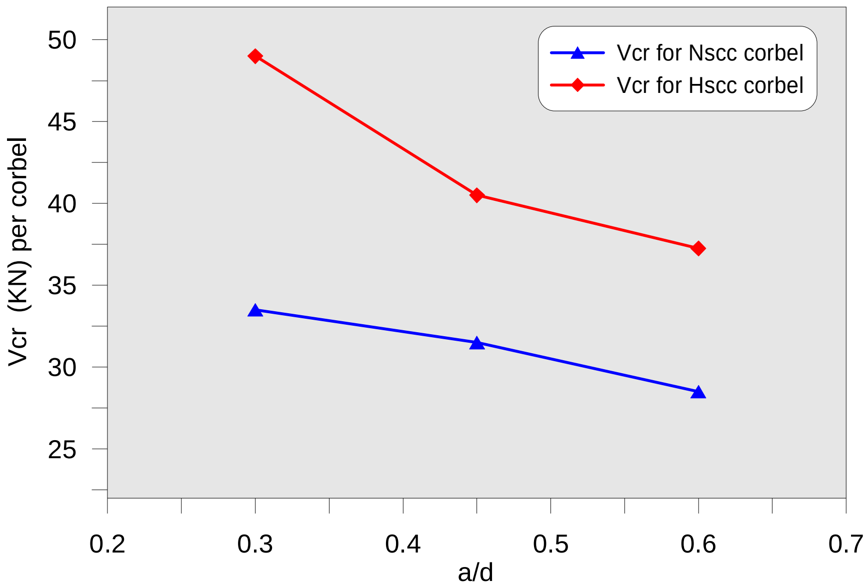


Fig .(14) Effect of shear span to effective depth ratio on cracking load of NSCC and HSCC corbels

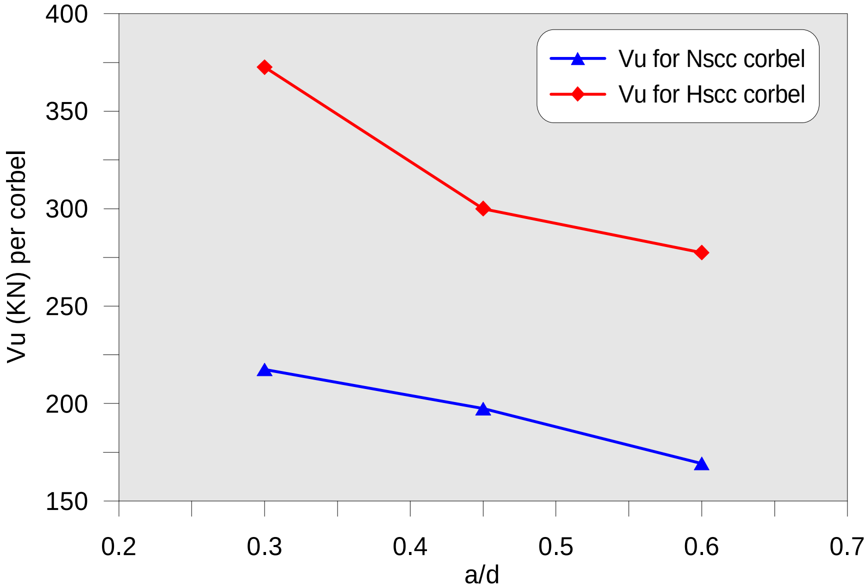


Fig .(15) Effect of shear span to effective depth ratio on ultimate load of NSCC and HSCC corbels

7.2 Effect of steel fiber content on cracking and ultimate shear capacity

Test result presented in **Table (5)** and **Figures (16)** and **(17)** indicate that the addition of steel fibers with shear span ratio to effective depth ratio (a/d=0.45) results in higher resistance against formation of the first crack for both types of concrete (NSCC and HSCC) corbels.

The cracking load and ultimate load for NSCC corbels increase by 31.5% and 25.3% when the volume of steel fibers increases from 0% to 0.4%. While the cracking and ultimate loads increase by 7.3% and 3.1% when the volume of steel fibers increases from 0.4% to

0.8% and the increase in volume of steel fibers from 0% to 0.8% results in increasing the cracking load and ultimate load by about 41.1% and 29.1% respectively.

Also, it was found that the cracking load and ultimate load for HSCC corbels increase by 32.7% and 26.9%, when the volume of steel fibers increases from 0% to 0.4%. While the cracking and ultimate loads increase by 8.8% and 7.2% when the volume of steel fiber increases from 0.4% to 0.8%. The increasing in volume of steel fibers from 0% to 0.8% results in increasing the cracking and ultimate loads by about 44.4% and 36.1% respectively.

From test results, it can be noted that the increase in the volume fraction of steel fibers leads to a significant improvement in the cracking and ultimate loads for both types of concrete (NSCC and HSCC). Steel fibers enhance the strength, delay the formation and propagation of cracks and hold the concrete parts across crack.

Table .(5) Effect of volume of fraction of steel fibers on cracking and ultimate loads for NSCC and HSCC corbels

Concrete type		The increase in the volume of steel fibers(V_f) %		
		% increase in load		
		0 to 0.4 %	0.4 to 0.8 %	0 to 0.8 %
NSCC	Vcr	31.5	7.3	41.1
	Vu	25.3	3.1	29.1
HSCC	Vcr	32.7	8.8	44.4
	Vu	26.9	7.2	36.1

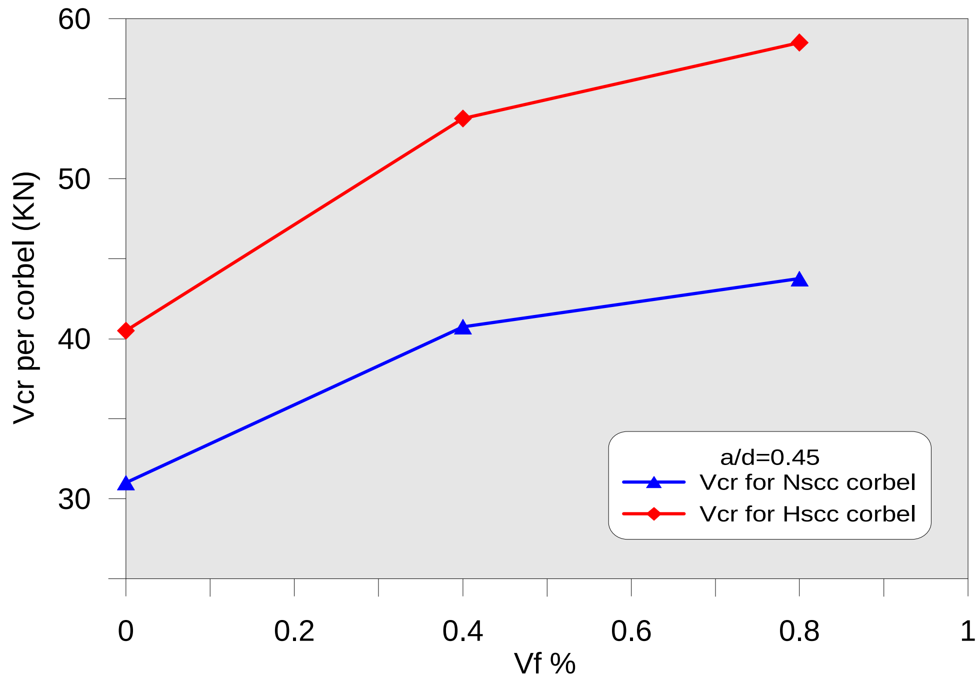


Fig .(16) Effect of volume of fraction of steel fibers on cracking load of NSCC and HSCC corbels

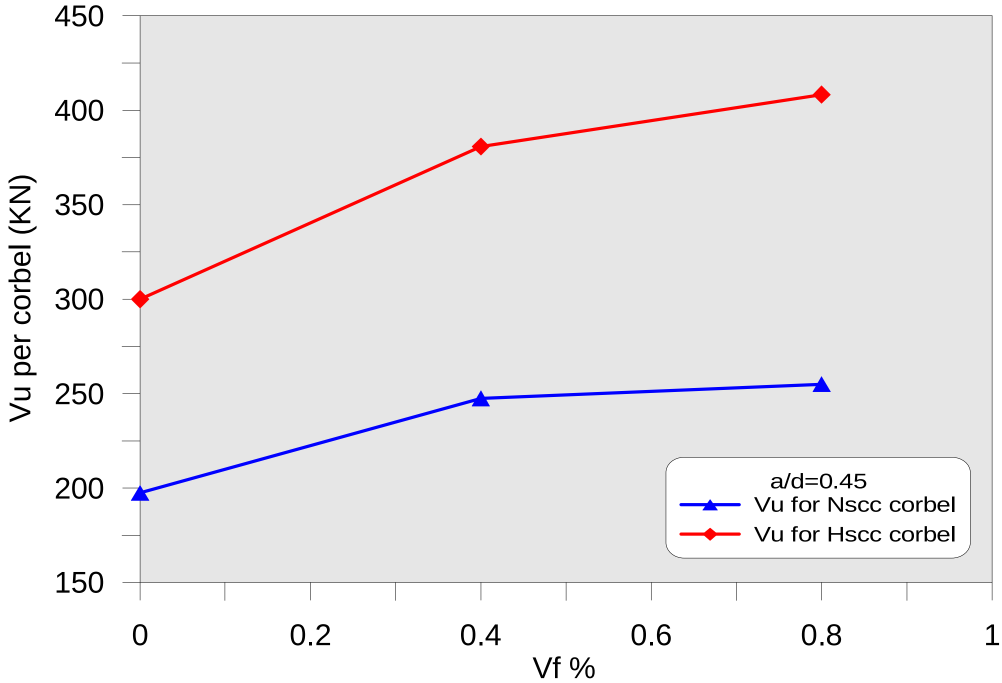


Fig .(17) Effect of volume of fraction of steel fibers on ultimate load for NSCC and HSCC corbels

8. Conclusions

1. It was found that for NSCC corbels, when the (a/d) ratio decreases from 0.6 to 0.45, have increase in cracking and ultimate loads of about 7.8% and 16.7 %. While when the (a/d) ratio decreases from 0.45 to 0.3, an increase in the cracking load and ultimate load of about 8.1% and 10.1% is achieved. Also, when the (a/d) ratio decreases from 0.6 to 0.3 an increase in the cracking and ultimate loads of about 16.5% and 28.5% is obtained.
2. For HSCC corbels, as the (a/d) ratio decreases from 0.6 to 0.45, an increase in cracking and ultimate loads of about 8.7% and 8.1% has been obtained. While when the (a/d) ratio decreases from 0.45 to 0.3, an increase in the cracking and ultimate loads of about 20.9% and 24.2% was achieved. Also, when (a/d) ratio decreases from 0.6 to 0.3 the increase in the cracking load and ultimate load is about 31.5% and 34.2%.
3. The cracking load and ultimate load for NSCC corbels increase by 31.5% and 25.3% when the volume of steel fibers increases from 0% to 0.4%. While the cracking and ultimate loads increases by 7.3% and 3.1% when the volume of steel fibers increases from 0.4% to 0.8% and the increase in volume of steel fibers from 0% to 0.8% results in increasing the cracking load and ultimate load by about 41.1% and 29.1% respectively.
4. It was found that the cracking and ultimate loads of HSCC corbels increase by 32.7% and 26.9%, when the volume fraction of steel fibers increases from 0% to 0.4%. While the cracking and ultimate loads increase by 8.8% and 7.2% respectively when the volume of steel fiber increases from 0.4% to 0.8%. The increasing in volume fraction of steel fibers

from 0% to 0.8% results in increasing the cracking and ultimate loads by about 44.4% and 36.1% respectively.

5. With increasing compressive strength by approximately 93.1% the cracking load and ultimate load improve by a range, from 28.6% to 46.3% and 51.9% to 71.3% (with average 34.0% and 60.2%) for NCC and HSCC respectively. It was found that the improvement is larges in fibrous corbels when compared with nonfibrous corbels.
6. The load-deflection response of self-compacting reinforced concrete corbels has been significantly affected by the (a/d) ratio. The response becomes appreciably nonlinear as the (a/d) ratio increases and the load- deflection response was slightly affected by the compressive strength of concrete.It was found that the response is slightly stiffer as ($f'c$) increases. Also, it is fairly affected by steel fibers content (v_f). The response becomes stiffer as fiber content increases especially when 0.8 % ratio of steel fibers is used and when the (a/d) ratio becomes larger.
7. It was found that the addition of steel fibers delays the formation of the cracking of fibrous corbel relative to nonfibrous corbels.
8. The addition of steel fibers increases corbels stiffness, thus reducing the deflection for a given load level.
9. The experimental results show that the improvement in the cracking capacity of self-compacting reinforced concrete corbels due to presence of steel fibers is larger than improvement in it due to increasing the concrete compressive strength

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