CONSTRUCTION
e-ISSN: 2785-8731
VOL. 2, ISSUE 1, 66 – 78
DOI: https://doi.org/10.15282/cons.v2i1.7608

ORIGINAL ARTICLE

Shear Resistance of Fibrous Reinforced Concrete Corbels - A Critical Review

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ABSTRACT – Reinforced concrete corbels have become a frequent attribute in building construction, with precast high-strength concrete increasing use. Corbels are short-hunched cantilevers that project from the inner face of columns or walls to support heavy concentrated loads or beam reactions. They are essential structural elements for supporting precast beams, girders, cranes, and other precast structure systems. This paper reviews the effect of fiber, shear span to depth ratio, concrete strength, and reinforcement ratio on the reinforced fibrous high strength concrete corbel's shear resistance in previous research. The results show that the shear resistance of corbels enhances with increasing main reinforcement, compressive strength, and the volume fraction of fibers, whereas it decreases with the improvement of the shear span-to-effective depth ratio of the corbel. In addition, using fibers in high-strength reinforced concrete corbel increases the ductility and thus defines the mode of failure of the corbels, depending on the fiber parameters.

ARTICLE HISTORY
Received: 07th Apr 2022
Revised: 15th Apr 2022
Accepted: 18th Apr 2022

KEYWORDS
Fiber content
Fibrous high strength
Reinforced concrete corbel
Shear span to depth ratio

INTRODUCTION

Designers have commonly preferred the precast reinforced concrete elements to construct buildings and bridges. As an example of such elements, corbels play a vital role in transferring loads from beams or slabs to columns or walls. Brackets or corbels project from a column or a structural wall or are the beam's overhanging portion. In most cases, the shear span-to-depth ratio of a corbel is equal to or less than one [1]. Corbels can be provided to support rails that transfer heavy loads from moving cranes in heavy-duty factory workshops. Corbels are also provided at the cantilevered end of the girders in double cantilever balanced reinforced concrete bridges to support the end spans of the bridge [2].

Corbels are designed mainly to provide for vertical reaction and sometimes for horizontal frictional forces. The reinforcement of the corbels is primary tension steel and horizontal bars, as shown in Figure 1. The horizontal reinforcement bars (stirrups) are used for shear resistance, whereas the top longitudinal bars are for flexural resistance.

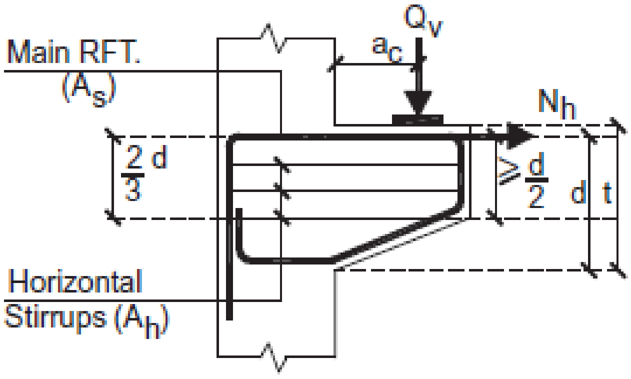

Figure 1. Details of steel reinforcement in corbels [3].

The reinforced concrete corbels display several failure modes. It is worth demonstrating the failure types in corbels, as shown in Figure 2. The common-mode failures are a diagonal shear failure, shear friction failure, anchoring splitting failure, vertical splitting failure, bearing failure, and bending failure. Diagonal shear failure starts under the concentrated load application and propagates toward the bottom corner junction of the bracket to the column face, as shown in Figure 2(a). Shear friction failure starts at the upper comer of the bracket or corbel and proceeds almost vertically through the corbel toward its lower fibers, as shown in Figure 2(b). Anchoring splitting failure occurs by rotating the end of a freely supported beam, as shown in Figure 2(c). Vertical splitting failure usually happens by direct tension due to horizontal load, as shown in Figure 2(d). Bearing failure occurs due to crushing the concrete under the load-bearing if the bearing area is not adequately proportioned, as shown in Figure 2(e). Bending failure occurs when the primary reinforcement yields, as shown in Figure 1(f) [4].

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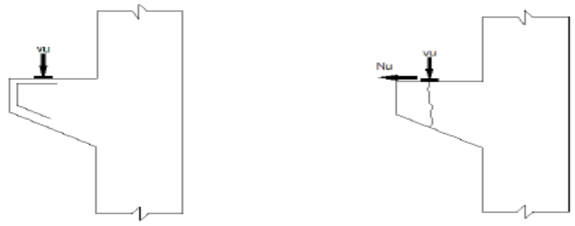
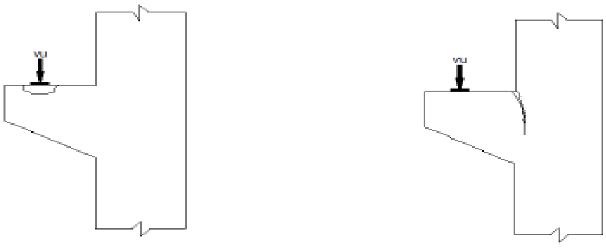
(a) Diagonal shear failure (b) Shear friction failure



(c) Anchoring splitting failure (d) Vertical splitting failure



(e) Bearing failure (f) Bending failure

Figure 2. Failure modes in RC Corbels.

Fibers in concrete can be considered reinforcements spread out all over the depth of a member. The addition of steel fibers to the concrete substantially increases the shear strength. The effectiveness of fiber reinforcement to increase shear resistance is dependent on several factors, including matrix properties, fiber properties (material properties, aspect ratio, and shape), fiber content, and bond stress versus slip response of fibers [2]. The most common fibers used in corbels are steel, glass, and carbon fibers.

Fiber application in concrete leads to enhancing the mechanical properties of concrete. It is considered suitable material to use, especially in corbels. The compressive and tensile behavior of fibrous concrete is highly dependent on fiber properties, mixing, curing, and concrete matrix [3, 5-7]. The stress is transmitted from the matrix to the fiber by shear deformation at the fiber-matrix interface. This transmission occurs due to the different mechanical properties of the fibers and the matrix. This effectiveness explains why fibers can be used to replace horizontal stirrups in high-strength concrete fiber corbels [6]. Under uniaxial compressive behavior, many experimental studies and numerical models are carried out to study the effect of fiber addition to normal and high-strength concrete. It was found that the increase in fiber volume fraction and fiber aspect ratio increases the ductility of the stress-strain curves. The compressive strength of the fibrous concrete slightly increased up to 9% greater than non-fibrous concrete [6]. This paper reviews the factors that affect fibrous reinforced concrete corbels' shear strength and behavior. Thus, several pieces of research have been reviewed, and their results are critically discussed in this paper.

LITERATURE REVIEW

The effect of shear span-depth ratio a/d

Abdel Hafez et al. [8] tested seventeen high strength reinforced-concrete corbels with the size of 150 x 150 x 200 mm with three fiber content (0, 1, and 1.5%) and three a/d ratios (0.45, 0.6, 0.75), three main reinforcement arrangements (2φ12, 2φ16 2φ18) without stirrups. It was found that with an increase in shear span-to-depth ratio from 0.45 to 0.75, the shear strength decreases up to 21.6%, as shown in Figure 3. It was noted that the fiber content addition leads to the improvement of the shear capacity for the fiber concrete corbels of the same a/d ratio. The shear load reduces by 3% and 6% (for a/d ratio of 0.6 and 0.75 concerning 0.45), respectively, with 1.0% fiber content. However, the deflection slightly increased with increasing a/d ratios. Concerning the 0.45 a/d ratio, the increase in a/d ratio results in an increase of 22% and 23%, respectively, in deflection at 0.9 Pu of corbels without fibers, which Pu is an ultimate load on a corbel, whereas the deflection increased by 42.3% and 44%, respectively, in deflection at 0.9 Pu of corbels with 1.0% fibers content. FattuhiI and Hughes [14] reported a decrease of 33% in failure load of normal strength concrete corbels without fibers and a decrease of 20% in failure load of normal strength concrete corbels with 1.0% fibers of increase in shear span-to-depth ratio from 0.59 to 0.83. It can also be noticed that improvement in ultimate load and ductility due to fibers content was more significant at a higher span-to-depth ratio.

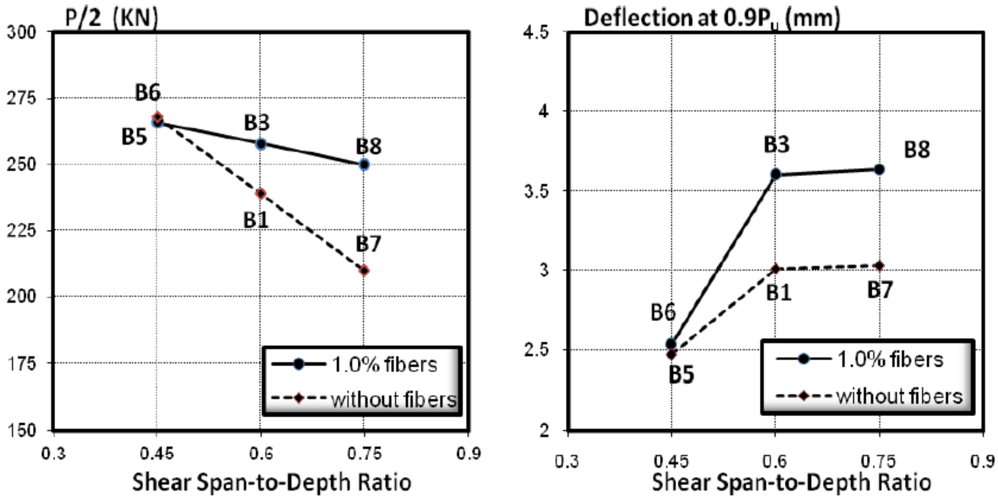


Figure 3. Effect of a/d ratio on shear load and deflection [8].

Kumar and Barai [9] present the relationship between the shear-span depth ratio and the predicted shear strength of SFRC corbels at three different compressive strength values of concrete f 0 c ¼ 30; 35 and 40 MPa. Other input parameters for the study are b = 150 mm, d = 200 mm, pt = 1.5%, Vf =2%, aspect ratio is 90 and a/d ratio being varied from 0.6 to 1.1. From Figure 4, it is observed that there is a decrease in the shear strength of corbels at an increasing value of the a/d ratio. This decrease in shear strength is 15.81%, 22.77%, and 28.06% at compressive strength of concrete f c =30; 35 and 40MPa, respectively, when the a/d ratio increases from 0.6 to 1.1. Therefore, the effect of the a/d ratio is more pronounced at higher values of compressive strength of concrete.

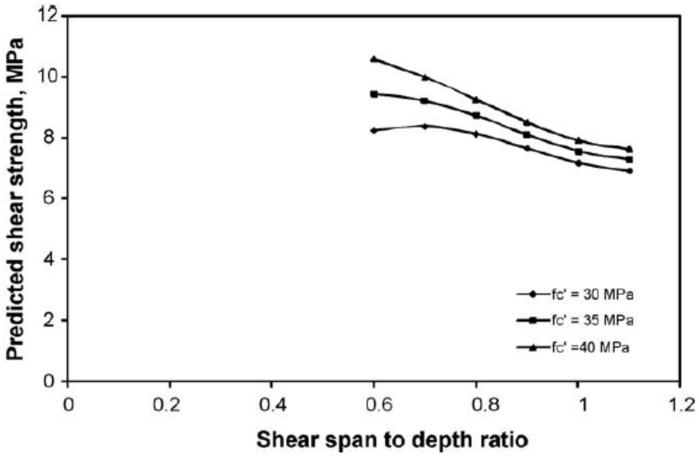


Figure 4. a/d ratio and predicted shear strength [9].

Salman et al. [10] tested ten specimens in which the shear span to effective depth ratio (a/d), the amount of steel fiber (Vf), and compressive strength(fc') of self-compacting concrete were varied. All specimens had the same length, thickness, and main reinforcement. They were subjected to concentrated vertical loads only. 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 exact value of main reinforcement, horizontal reinforcement, and the strength and type concrete. It was found that for normal self-compact concrete NSCC corbels, when the (a/d) ratio decreases from 0.6 to 0.45, an increase in cracking load (Vcr) and ultimate load (Vu) of about 7.8% and 16.7 % is obtained. When the shear span to depth ratio decreases from 0.45 to 0.3, shear capacity increases the cracking load and an 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. When the (a/d) ratio decreases from 0.45 to 0.3, the cracking load and ultimate load increase of about 20.9% and 24.2% are achieved. Also, when the (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 Figures 5 and 6.

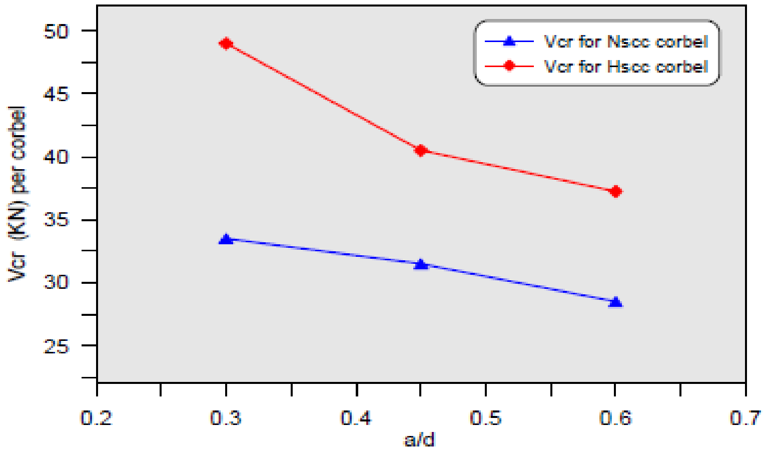


Figure 5. Effect of a/d ratio on cracking load [10].

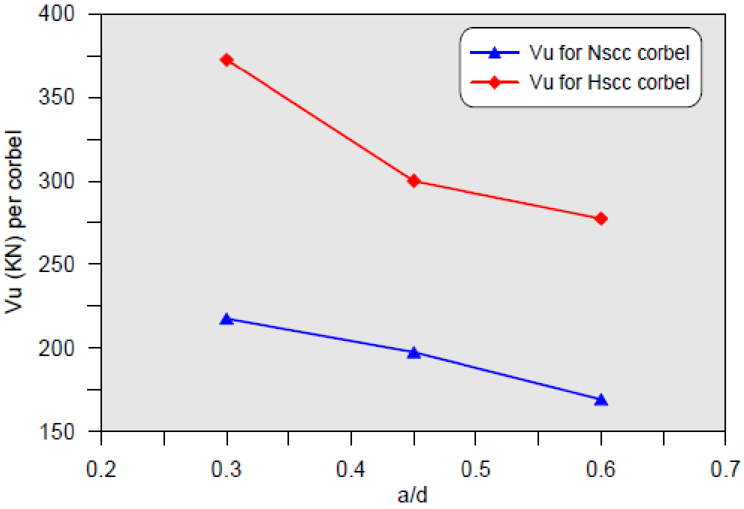


Figure 6. Effect of a/d ratio on failure load [10].

EFFECT OF COMPRESSIVE STRENGTH

Abdel Hafez et al. [8] reported that the compressive strength of concrete has a positive effect on shear failure load, as shown in Figure 7. An increase in concrete strength from 62.7 N/mm^2 to 70.5 N/mm^2 and 106.5 N/mm^2 results in 17.7% and 25.6% respectively in failure load and a decrease of 6.8% 9.6% respectively in deflection at 0.9 Pu of corbels without fibers. Moreover, an increase in concrete strength from 65 N/mm^2 to 82 N/mm^2 and 106 N/mm^2 results in an increase of 17.3% and 19.1%, respectively, in failure load and a decrease of 10.4% and 12.2%, respectively, in deflection at 0.9 Pu of corbels with 1.0% fibers content.

Yong and Balaguru [11] also reported an increase of 14.3% in the failure load of corbels without fibers. In case of an increase in concrete strength from 39 N/mm^2 to 54.7 N/mm^2. It can also be noticed that the improvement in ultimate load and ductility due to the presence of fibers content was more significant in those with higher concrete strengths.

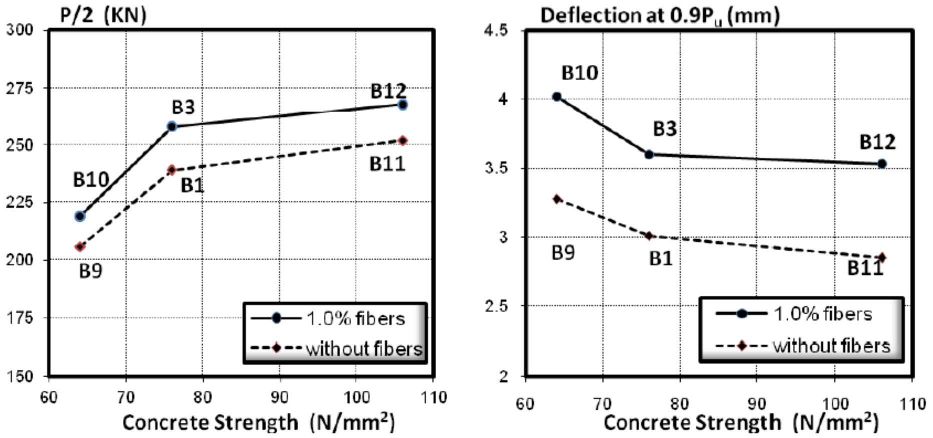


Figure 7. Effect of concrete strength on shear load [8].

Khaleel et al. [12] tested ten corbels with different compressive strengths with and without carbon fibers. They reported that an increase in compressive strength of tested corbels causes an increase in the cracking and ultimate loads of the tested corbels, as shown in Table 1. The percentage increase in the ultimate loads was about 27.5% and 32.3%, while cracking loads were more than 40% when concrete compressive strength increased from 37.1 MPa to 52.0 MPa, for ρh.fyh, which ρh.fyh is a horizontal reinforcement index, values equal to 1.070 and 2.141 MPa respectively. the ultimate shear strength increased about 28.2%, 29.6%, and 31.4% when concrete compressive strength increased from 37.1 MPa to 52.0 MPa in the absence of stirrups and for volume fraction 0%, 0.2%, and 0.4% respectively. While for the same corbels, the shear cracking loads increased about 27.2%, 28.6%, and 28.7%.

Table 1. The effect of the horizontal reinforcement index and concrete compressive strength on the shear capacity of fibrous reinforced concrete corbels [12].

Group	Specimen No.	Fc',MPa*	ρh.fyh, MPa	Fiber content, %	1 st cracking load, kN	Increase in first cracking load, %	Ultimate load, kN	Increase in ultimate load, %
A	A1	37.1	0.000	0.0	81	--	227	--
	A2		1.070		93	14.8	247	8.8
	A3		2.141		105	29.6	260	14.5
	A4		0.000	0.2	105	29.6	230	1.3
	A5			0.4	136	67.9	242	6.6
B	B1	52.0	0.000	0.0	103	--	291	--
	B2		1.070		136	32.0	315	8.2
	B3		2.141		150	45.6	344	18.2
	B4		0.000	0.2	135	31.1	298	2.4
	B5			0.4	175	69.9	318	9.3

*: cylinder concrete compressive strength is taken as 0.8 of cube concrete compressive strength

Beshara et al. [13] numerically analyzed three steel fiber reinforced concrete (SFRC) corbels with different concrete compressive strengths (fc`) (30, 40, and 52.9 MPa) for (S1, S2, and S3), respectively. The load-deflection curves and the load-steel strain curves for the analyzed specimens are shown in Figure 8. The comparison between the results indicates that increasing fc` enhances shear capacity (Vu) by 27% and 45% for specimens S2 and S3 compared to S1. Also, it increases the longitudinal steel strain (εs) for corbels S2 and S3, respectively, by 70% and 84% compared to specimen S1. The calculated strain ductility factor (μs) is 1.2, 4, and 7 for S1, S2, and S3, respectively. Then, the strain ductility (μs) increased due to increased concrete compressive strength (fc`). Significant enhancement in the toughness (I), calculated as the area under the load-deflection curve, is observed due to the increase of fc`. Toughness is enhanced by 54% and 107% for specimens S2 and S3, respectively, compared to specimen S1. It was found that increasing (fc') delays the possibility of premature shear failure for SFRC corbels.

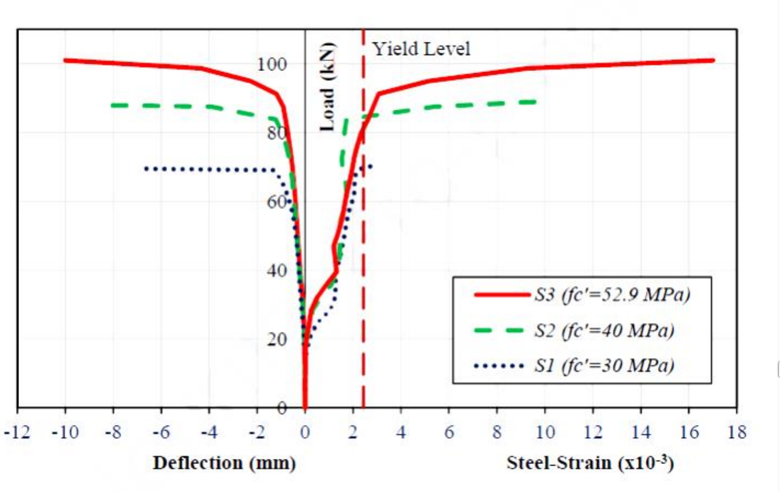


Figure 8. Predicted load-deflection -steel strain for the corbels [13].

EFFECT OF FIBER CONTENTS

Abdel Hafez et al. [8] reported that an increase in steel fiber contents from 0% to 1.0% and 1.5% results in an increase in ultimate capacity by 19% in the failure load of the corbel. However, this increase increases from 20% to 45% respectively in deflection at 0.9 Pu of corbels, as shown in Figure 9. Similar results were reached that an increase of 7.3% in failure load was recorded by Fattuhil and Hughes [14] in the case of corbels made of normal strength concrete. This behavior confirms the effect of fiber in improving the ductility of high-strength concrete.

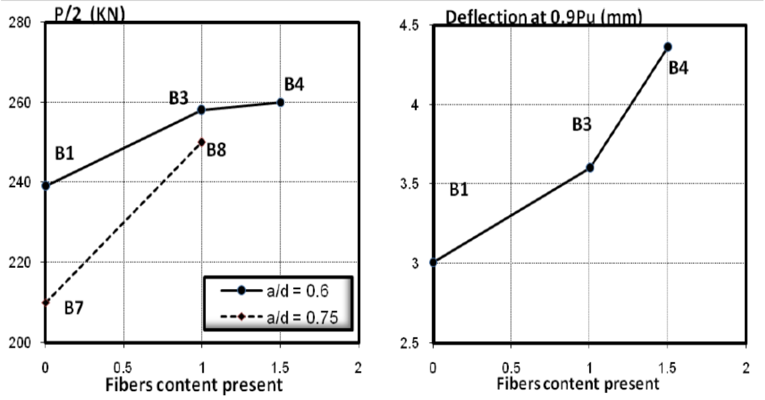


Figure 9. Fiber contents vs. shear failure load [8].

Khaleel et al. [12] revealed that the addition of carbon fibers for their corbels resulted in higher resistance against the formation of the first crack. The first crack loads for non-fibrous concrete specimens were 81 kN and 103 kN for corbels with normal and moderately high strength concrete, respectively, as shown in Figure 10, where Group A is normal concrete and Group B is high strength concrete. The values increased by 29.6% and 31.1% due to 0.2% carbon fibers. At the same time, the percentage increases in the first shear cracking loads were 67.9% and 69.9% due to the presence of carbon fibers at 0.4%. The results indicated that adding carbon fibers could significantly enhance the corbel's first shear cracking load.

The results indicated that carbon fibers slightly enhanced the ultimate corbel load. Furthermore, it can be indicated that the presence of carbon fibers has a slight effect on the ultimate load capacity of tested corbels compared with an enhancement that occurred in the first cracking loads. The ultimate loads for non-fibrous concrete specimens were 227 kN and 291 kN for normal and moderately high strength concrete, respectively, as presented in Figure 11. The percentage increases in ultimate loads were 1.32% and 2.4% due to 0.2% carbon fibers, respectively. Finally, the percentage increases in the ultimate loads were 6.6% and 9.3% due to carbon fibers at 0.4%.

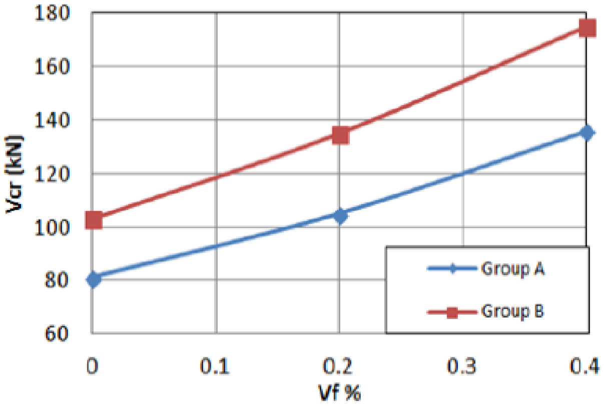


Figure 10. Carbon fiber content vs. cracking shear load [12].

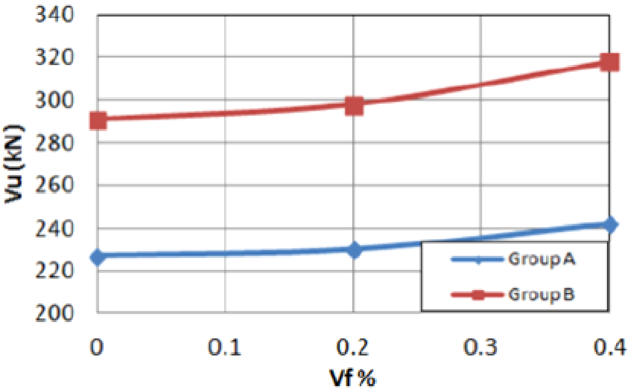


Figure 11. Carbon fiber contents vs. shear failure load [12].

Kumar and Barai [9] numerically studied the behavior of predicted shear stress at failure for three values of compressive strength of the concrete composite, i.e., f 0c ¼ 30, 35, and 40 MPa. The other input parameters are b = 150 mm, d = 200 mm, a/d ratio = 0.8, pt = 1.5% and lf/df ratio = 90 and v f being varied from 0.5 to 2.0%. This behavior of the network model is also correct because, for a particular value of compressive strength of concrete, compressive strength remains constant even though the value of volume fraction of fibers increases from 0.5 to 2.0%. Keeping all other input parameters the same as mentioned above, the value of Vf is varied between 0 and 2.5% in Figure 12. In the figure, the shear strength increase is more at a lower value of compressive strength of concrete for all three different types of concrete strength (fc' =30; 35 and 40MPa at v f ¼ 0%). The average increase in shear strength, in this case, is about 13% when v f is increased up to 2.5%, which implies that shear strength finally depends on the increase of compressive strength of concrete when the volume fraction of fibers in concrete is altered.

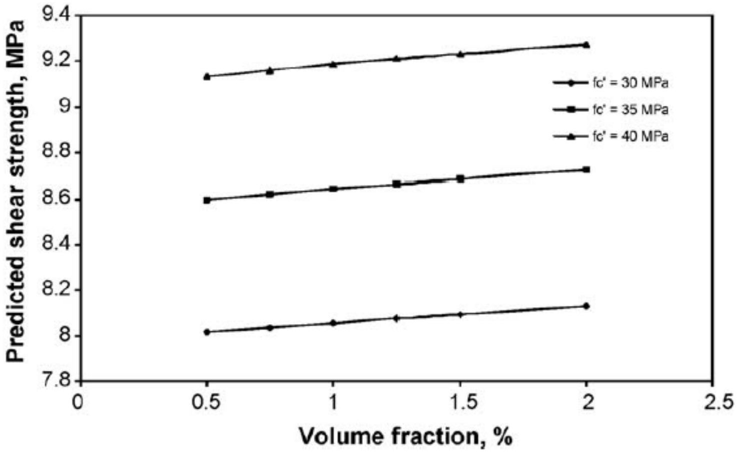


Figure 12. Fiber volume vs. predicted shear strength [9].

Beshara et al. [13] analyzed three steel fiber reinforced concrete SFRC corbels with different fiber volumes (Vf). The fiber volumes are considered as (0.0%, 0.5%, and 1.0%) respectively for corbels (S4, S5, and S6). the predicted response curves (shear-deflection and shear-steel strain) for the specimens are shown in Figure 13. An enhancement in the shear capacity (Vu) by 15% and 31% have been observed for S5 and S6, respectively, compared with S4. Also, significant improvement in the toughness (I) and strain ductility (μs) is noticed. Compared to specimens, the predicted increase in the toughness (I) is 171% and 513% for specimens S5 and S6, respectively. The predicted values of strain ductility (μs) are 3.5, 6, and 7 for specimens S4, S5, and S6, respectively. The strain of the tension reinforcement (εs) is enhanced by providing higher fiber volume (Vf). As clarified in the load steel strain curves, εs are enhanced for specimens S5 and S6 by 73% and 102%, respectively, compared to specimen S4. The predicted crack patterns are shown in Figure 17 for specimens S4, S5, and S6. Increasing fiber volume delays premature shear failure for corbels and increases crack propagation at corbel length and depth.

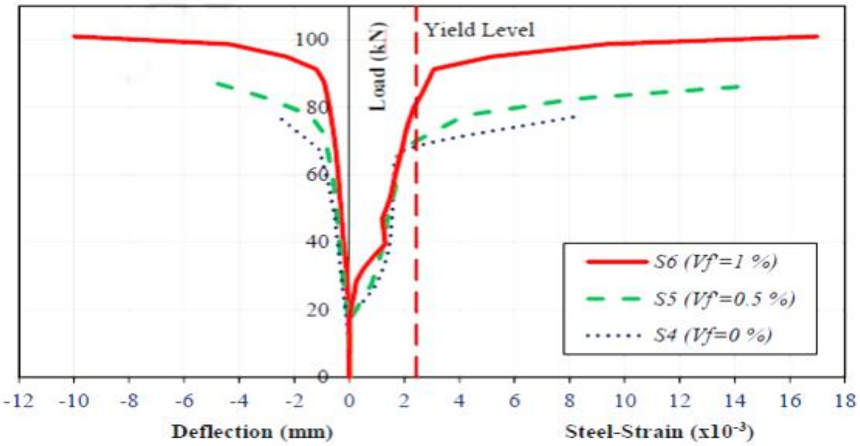


Figure 13. Predicted responses for the corbels [13].

Salman et al. [10] reported that the addition of steel fibers with shear span ratio to effective depth ratio (a/d=0.45) results in higher resistance against the formation of the first crack for both types of concrete (NSCC and HSCC) corbels. Steel fibers enhance the strength, delay cracks' formation and propagation, and hold the concrete parts across the crack. 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%, as summarised in Table 2. In comparison, 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 the 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%.

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). The increase in the volume of steel fibers from 0% to 0.8% improves the cracking and ultimate loads by about 44.4% and 36.1%, respectively. In contrast, the cracking and ultimate loads increase by 8.8% and 7.2% when steel fiber volume increases from 0.4% to 0.8%.

Table 2. Effect of steel fiber contents on cracking and ultimate shear loads.

Concrete type	Shear strength at the crack and ultimate loads	The increase in the volume of steel fibers (Vf)%		
		% 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

THE EFFECT OF REINFORCEMENT

Abdel Hafez et al. [8] reported that the main reinforcement ratio affects both shear failure and deflection, as shown in Figure 14. It was noted that an increase in main steel reinforcement ratio from 1.16% to 2.06% and 2.61% results in an increase of 54.2% and 65.2%, respectively, in failure load of corbels without fibers and an increase of 22.3% in failure load of corbels with 1.0% fibers content. However, this increase leads to a decrease of 4.7% in deflection at 0.9 Pu of corbels without fibers and an increase of 12.9% and 19.1%, respectively, in deflection at 0.9 Pu of corbels with 1.0% fibers content.

The addition of fibers reduces the effect of the multi-axial state of stress, yielding stress in steel bars and resulting in higher ductility. Fattuhil and Hughes [14] also revealed an increase of 89% in failure load of corbels without fibers and an increase of 67% in failure load of corbels with 1.0% fibers obtained in case of increase in main steel reinforcement ratio from 0.51% to 1.16%. It can be then noticed that improvement in ultimate load due to increased fibers content was more significant in lower main steel reinforcement ratios.

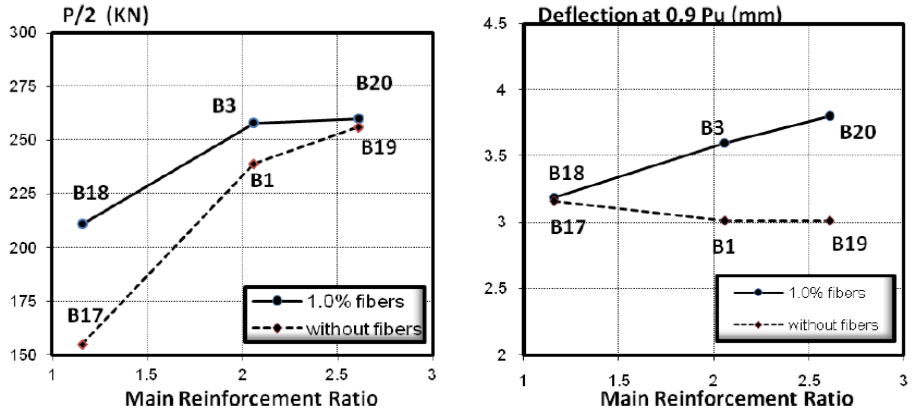


Figure 14. Main reinforcement ratio vs. sheal load and deflection [8].

Kumar and Barai [9] studied the relationship between longitudinal steel ratio and predicted shear strength by ANN model MB at three different fc = 30, 35, and 40MPa, as shown in Figure 15. The other input parameters are b = 150 mm, a/d = 0.7, v f = 2:0%, lf/df = 90 and pt being varied from 0.5 to 1.6% From figure it is seen that the value of pt up to 1.3%. there is a sharp increase in the shear strength of corbels, and beyond that, the shear strength of corbels is almost constant for fc’ = 30 and 35MPa, whereas the marginal increase is still found for fc’ = 40 MPa. For an increase in the value of pt from 0.5 to 1.3%, the value of shear strength of corbel increases by 150.9% at fc’ = 30 MPa, 140.0% at fc’ = 35MPa, and 121.2% at fc’ = 40MPa, which shows the rate of increase of shear strength are more pronounced at lower values of compressive strength of concrete.

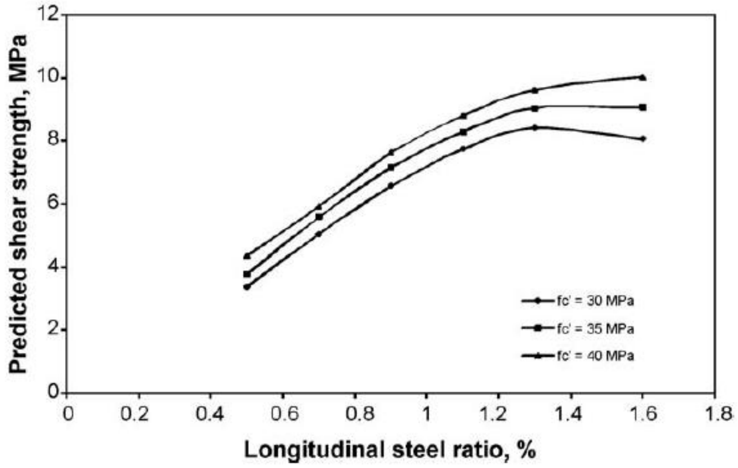


Figure 15. Main steel reinforcement ratio vs. predicted shear strength [9].

Abdel Hafez et al. [8] reported that when horizontal steel reinforcement (stirrups) is presented, both the ultimate load and maximum deflection have been increased by 8.4% in failure load and 5% at corresponding deflection of 0.9 Pu of corbels without fibers, as shown in Figure 16. However, an increase of 0.8% in failure load and 11.1% deflection at 0.9 Pu recorded corbels with 1.0% fibers. It can also be noticed that improvement in ultimate capacity due to increased fiber content was more significant in corbels without horizontal stirrups.

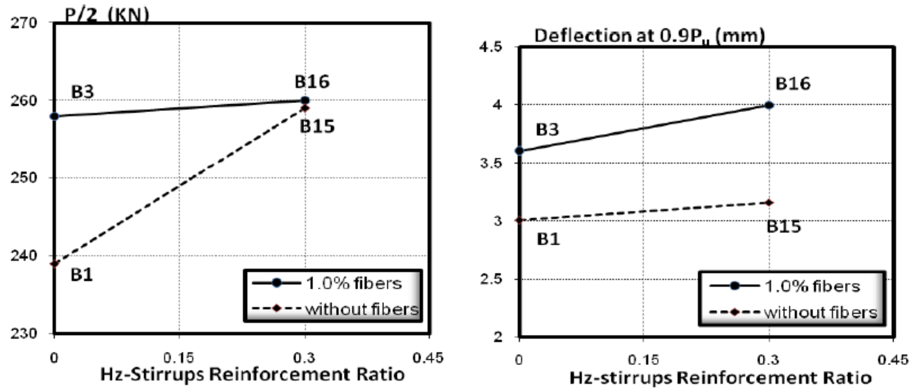


Figure 16. Effects of stirrups on shear load and deflection.

Khaleel et al. [12] also revealed the effect of horizontal reinforcement ratio for the non-fibrous normal strength concrete corbels (Group A), as previously presented in Table 1. the increase in the amount of ρh.fyh from 0 to 1.070 MPa caused an increase in the cracking and ultimate load of about 14.8% and 8.8% respectively. While the increase of ρh.fyh from 0 to 2.141 MPa caused an increase of 29.6% and 14.5%, respectively. For the non-fibrous moderately high strength concrete corbels (Group B), the increase in the amount of ρh.fyh from 0 to 1.070 MPa caused an increase in the cracking and ultimate load of about 32.0% and 8.2%, respectively. By increasing ρh.fyh from 0 to 2.141 MPa, the cracking and ultimate load was caused by about 45.6% and 18.2%, respectively.

It can be concluded that both the main reinforcement ratio (longitudinal flexural bars) and horizontal reinforcement ratio (stirrups) have played a significant role in the increase of shear capacity and reduction in deflection for non-fiber concrete. However, this effect has become negligible while fiber content is present in the concrete.

RESULTS AND DISCUSSIONS

Table 3 summarizes the test programs considered by the cited papers. The effects of several variables were studied, such as fiber contents, fiber types, concrete strength, a/d ratio, and horizontal and main reinforcement ratios. Steel, carbon, and glass fiber were mainly used to enhance the shear load in corbels. The fiber ratios (Vf) ranged from (0 to 4%) for steel (0 to 0.4) for both glass and carbon fibers. Different corbel dimensions were used in the previous works. The width of the corbels (b) was between 120 -200 mm, whereas the depth of the corbel (h) ranged from 150 to 370 mm. to facilitate the testing of the corbels, two corbels were commonly attached to the column, as shown in Figure 17. The corbel bearing surface is inverted and tested on the supporting system in this system. However, one corbel may be attached to the column in the construction, such as that corbel used to support the crane girder.

The compressive strength (fc) ranged from normal concrete to ultra-high-strength, 32 to 150 MPa. The effects of concrete compressive strength were considered with and without fibers. Different reinforcement ratios (ρ) were considered in the tests, ranging from 0 to 1.34%. In some tests, the stirrups were not used mainly while the concrete contains fiber. One of the repeated variables was shear span to depth a/d ratio. This ratio varied from 0.18 to 1.

Experimental shear loads (Vu) have been changed according to the variables. Shear load significantly decreased with increasing a/d ratio [15,16, and 17]. According to the results obtained by Gao and Zhang [15], the shear load is 820 kN at an a/d ratio equal to 0.18, whereas the shear load is reduced to 279 kN at an a/d ratio equal to 0.79. the reduction is about 193% for the same condition with 1% steel fiber. In addition, the results obtained by Ridha et al. [16] show that shear load is 813 kN at an a/d ratio equal to 0.4, whereas shear load is reduced to 456 kN at an a/d ratio equal to 0.8. for the same condition without fiber.

Fiber contents also improved the shear capacity of the corbels. It was noted that experimental shear load increased with increased steel fiber contents to restricted content. Referring to Iliyas et al. [18], the shear load increased up to 2.5% steel fiber compared with the control specimen (0% steel fiber). Beyond 2.5% to 4%, the shear load reduced again. The shear load is about 201 kN at 0% fiber, whereas the shear load becomes 400 kN at 2.5% fiber. The shear load suddenly decreased to 275 at 3% fiber. The low values at high fiber contents could be due to the balling of the fiber and inadequate mixing.

Khaleel et al. [12] showed that the shear load slightly increased from 227 kN at 0% carbon fiber to 240 kN at 0.4% carbon fiber without horizontal reinforcement. Moreover, Kamil [19] and Abdi [17] reported similar results for glass fibers. The results obtained by Kamil [19] showed that the shear load negligibly increased from 101 kN at 0% glass fiber to 114 kN at 0.4% glass fiber. It can be concluded that both carbon and glass fiber has a negligible effect on shear load capacity with increasing fiber content.

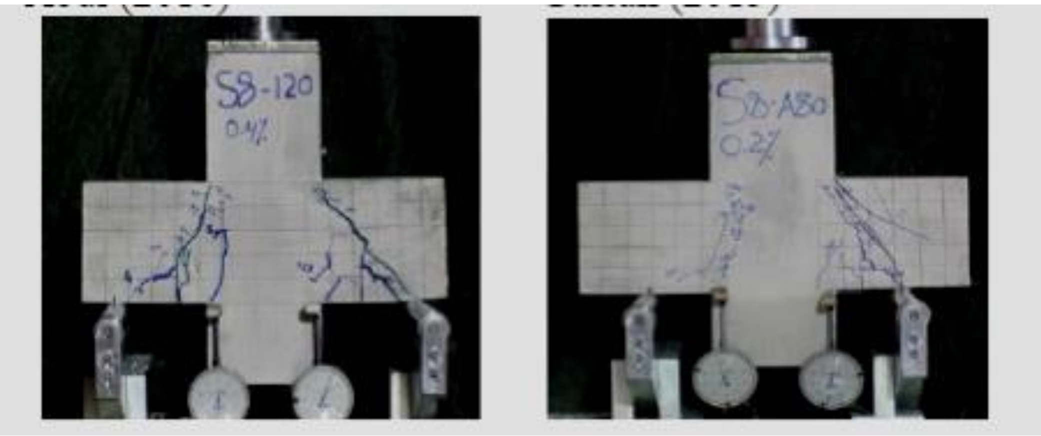


Figure 17. Test setup and crack pattern [19].

Table 3. Variables and test results from the literature.

Ref.	Corbel designation	Fiber type	Vf, %	Asm mm^2	Ash,mm^2	ρ,%	fc, MPa	b, mm	H, mm	a/d	Vu,kN
Gao and Zhang [15]	SCP-40-0	steel	0			1.01	32	200	300		500
	SCP-40-0.5		1			1.01	32				390
	SCP-40-1.0		1.5			1.01	32				579
	SCP-40-1.5		2			1.01	32				637.5
	SCP-40-2.0		1			1.01	32				610
	SCP-30-1.0		1			1.01	24				461.5
	SCP-50-1.0		1			1.01	40				700
	SK-0.18		1			1.01	32			0.18	820
	SK-0.36		1			1.01	32			0.36	600
	SK-0.54		1			1.01	32			0.54	480
	SK-0.71		1			1.01	32			0.71	300
	SK-0.79		1			1.01	32			0.79	249
Iliyas et al., [18]	M-0	steel	0	226	202	NA	NA	150	370	0.547	200.8
	M-0.5		0.5			NA	NA			0.549	225.2
	M-1		1			NA	NA			0.533	330.6
	M-1.5		1.5			NA	NA			0.517	320.5
	M-2		2			NA	NA			0.504	363.2
	M-2.5		2.5			NA	NA			0.494	399
	M-3		3			NA	NA			0.6	275.6
	M-3.5		3.5			NA	NA			0.556	272.4
	M-4		4			NA	NA			0.53	311.9
Ridha et al. [16]	C1G1	steel	2.3	226	0	0.74	150	250	150	0.4	813
	C2G1,3		2.3	226	0	0.74	150			0.6	611.6
	C3G1		2.3	226	0	0.74	150			0.8	456.5
	C4G2		2.3	226	100.5	0.74	150			0.4	829.3
	C5G2,4		2.3	226	100.5	0.74	150			0.6	645
	C6G2		2.3	226	100.5	0.74	150			0.8	473.3
	C7G3		2.3	100.48	0	0.33	150			0.6	506.3
	C8G3		2.3	401.9	0	1.32	150			0.6	701.7
	C9G4		2.3	100.48	100.5	0.33	150			0.6	522.2
	C10G4		2.3	401.9	100.5	1.32	150			0.6	727.5
	C11G3		2.3	NA	0	0	150			0.6	NA

Table 4. Variables and test results from the literature (cont.)

Ref.	Corbel designation	Fiber type	Vf, %	Asm mm^2	Ash,mm^2	ρ,%	fc, MPa	b, mm	H, mm	a/d	Vu,kN
Khaleel et al. [12]	A1	carbon	0	339.12	0		37.1	120	250	0.591	227
	A2				28.26						247
	A3				56.52						260
	A4		0.2		0						230
	A5		0.4		0						242
	B1		0		0		52				291
	B2				28.26						315
	B3				56.52						344
	B4		0.2		0						298
	B5		0.4		0						318
Kamil [19]	S8-80	Glass	0		80	0.53	92.79	150	150	0.66	101
	S8-100				100	0.56				0.84	72.8
	S8-120				120	0.53				0.99	64.9
	S8-80-0.2		0.2		80	0.53	83.76			0.63	110.5
	S8-100-0 .2				100	0.54				0.8	88
	S8-120-0 .2				120	0.53				0.95	71.8
	S8-80-0.4		0.4		80	0.53	88.26			0.63	114
	S8-100-0 .4				100	0.54				0.8	98.5
	S8-120-0 .4				120	0.54				0.96	76.3
Abdi [17]	S8-A80	Glass	0		80	0.55	61.33	150	150	0.66	79.5
	S8-A100				100	0.55				0.83	68.5
	S8-A120				120	0.55				0.99	51.85
	S8-A80-0.2%		0.2		80	0.53	52.6			0.63	78.9
	S8-A100-0.2%				100	0.53				0.79	73.5
	S8-A120-0.2%				120	0.53				0.95	69.2
	S8-A80-0.4%		0.4		80	0.53	56.3			0.63	98.3
	S8-A100-0.4%				100	0.53				0.79	77
	S8-A120-0.4%				120	0.53				0.95	63.5

CONCLUSIONS

Several studies have been done on fiber-reinforced concrete corbels, considering fiber content, shear span to depth ratio, concrete strength, and reinforcement ratio. The following conclusions can be drawn:

1. An increase in the shear span to depth ratio of corbels reduces of shear capacity of the corbel. For instance, an increase in shear span-to-depth ratio from 0.45 to 0.6 and 0.75 has decreased by 10.4% and 21.6%, respectively. Also, when the (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.
2. Compressive strength has effects on both shear load and deflection. Concrete strength increased from 62.7 MPa to 70.5 Mpa, and 106.5 MPa increased 17.7% and 25.6%, respectively, in shear capacity load and a decrease of 6.8% and 9.6% in deflection for corbels without fibers.
3. It can be concluded that both carbon and glass fiber has a negligible effect on shear load capacity, whereas steel fiber has a greater effect on increasing sheal load capacity.
4. The addition of steel fibers improves the shear strength of the tested corbels and increases the stiffness of these corbels. This improvement in the corbels, including stirrups, is more significant than those without stirrups.

5. The improved shear strength of tested corbels was significant for those with low main reinforcement ratios, large shear span-to-depth ratios, or lower concrete strength. Increasing the main reinforcement increases the ultimate shear strength and leads to a more ductile failure, especially when the fiber is presented.
6. It was found that the addition of steel fibers delays the formation of the cracking of fibrous corbel relative to non-fibrous corbels. The addition of steel fibers increases corbels stiffness, thus reducing the deflection for a given load level.
7. Both main reinforcement ratio (longitudinal flexural bars) and horizontal reinforcement ratio (stirrups) have significantly increased shear capacity and reduced deflection for non-fiber concrete. For the non-fibrous HSC corbels, it was found that the increase in the amount of ρh.fyh from 0 to 1.070 MPa caused an increase in the cracking and ultimate load of about 32.0% and 8.2%, respectively.

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