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EXPERIMENTAL STUDY OF SIFCON CORBELS

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ABSTRACT

In the current paper, results of testing four SIFCON corbel specimens under the effect of vertical load are reported. The shear span to effective depth ratio (a/d) was varied (0.35 to 1.0) and the fractional volume of the steel fibers was constant at 6% by volume of concrete. Two of the SIFCON corbels were reinforced with main reinforcement steel bars. The ultimate load, cracking load, deflection, failure mode, and crack patterns are negatively affected by the increased value of (a/d) and improved as the main steel bars are included in the SIFCON corbels.

Key words: SIFCON, corbels, concrete, steel fiber, reinforcement, shear span, effective depth, load.

INTRODUCTION

Corbels can be defined as the portions of the columns that overhang from their faces and are primarily designed to withstand the vertical shear pressures exerted on them by beams, as well as the severe horizontal forces resulting from shrinkage of the beams, creep, or a change in temperature. When designing corbels, it is possible to eliminate the effect of the horizontal loads by taking a number of aspects into account. Corbels are common design elements, and their importance and widespread use have grown significantly in recent years as the use of precast concrete structures and bridges has grown [1,2].

Corbels are often reinforced with main tension steel bars, framing steel bars, and a horizontal hoop. To improve shear capabilities and minimize the likelihood of abrupt collapse, horizontal stirrups are utilized along the depth of the corbels, as well as steel fibers have been utilized instead of secondary reinforcement. The performance of the corbels in terms of stiffness, ductility, crack width, and load-carrying capacities improved significantly as the amount of steel fiber increased. It was also found that the failure mechanism of the fibrous concrete corbels was either inclined shear or flexure, and the failure mode was more gradual [3-6].

In the current study, slurry infiltrated fiber concrete (SIFCON) corbels have been adopted. SIFCON is a special type of fibrous reinforced concrete (FRC), but with a larger content of steel fiber ranging from 4 to 20%, whereas FRC contains fibers in amounts ranging from 1 to 3%. SIFCON is produced without the addition of coarse aggregates of any type, even the coarse particles of sand. Furthermore, SIFCON includes a higher proportion of cement and water than traditional concrete. SIFCON can be prepared by placing fibers into formwork molds to the desired volume percentage or to the capacity of the mold. The resultant fiber bed is penetrated with a cement slurry or mortar with the aid of vibration or compaction to ensure complete infiltration and minimize the formation of honeycombs and clogging of fibers. Due to its high fiber content, SIFCON exhibits exceptional mechanical properties in terms of ductility and energy absorption. Therefore, it has been effectively used in seismic-resistant reinforced concrete members, pavement overlays, blast-resistant buildings, safe vaults, and bridge rehabilitation projects [7–12].

In this experimental work, The SIFCON corbels are casted with and without main tension steel bars and tested under the effect of vertical load with varied values of shear span to depth ratio. This study is handled to introduce more information about the design criteria of SIFCON corbels and to clarify the ability of using SIFCON instead of the secondary reinforcement.

EXPERIMENTAL INVESTIGATION

Four double-sided SIFCON corbels were casted and tested under the effect of vertical load only to study the structural characteristics, general behavior and cracking patterns, failure mode, load-deflection response, ultimate load, cracking load.

The dimensions of the specimens were constant; the depth of the trapezoidal corbel is 250 mm, the projection length of 250 mm, and the thickness of 125 mm at the free end and 250 mm at the column face, and the dimensions of the column are 150 mm in depth, 200 mm in width, and 650 mm in length.

The shear span to the effective depth ratios are 0.35 and 1, while the fractional volume of steel fiber was kept constant at 6% by the volume of the corbel.

Two of the specimens have been reinforced with three main steel bars of 12 mm in diameter on the tension side of the corbel. The transverse steel bars are eliminated. The column is reinforced with four main steel bars of 10 mm in diameter at the corners and five closed ties having a diameter of 8 mm with 150 mm center to center spacing. Figure [1] shows the dimensions and reinforcement details of the SIFCON corbels.

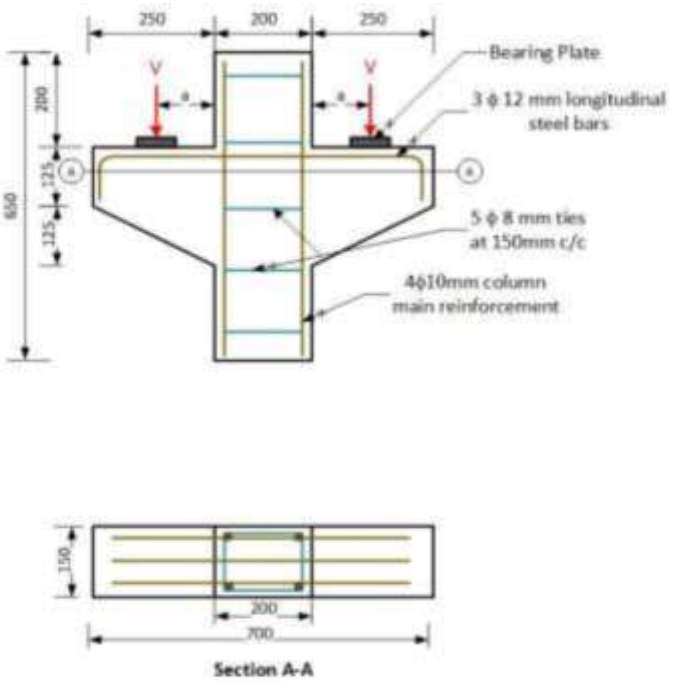


Figure 1: Details of the corbel specimen (all dimensions are in mm)

MATERIAL PROPERTIES

In the current investigation, ordinary Portland cement and natural sand passing through a 1.18 mm sieve are used in order to prepare the SIFCON mix. Several trail mixes were carried out to choose the proper amount of both the superplasticizer and the silica fume. The superplasticizer is chloride free and known as (Visco-Crete-5930L) and conforms to both ASTM C 494 [13] and BS EN [14] requirements, whilst the silica fume is confirmed to ASTM C 1240 [15] requirements.

Hooked end steel fibers of 35 mm length and 0.55 mm diameter are utilized in a fractional volume equal to 6% by volume. It complies with the requirements of ASTM C 1550-05 [16]. The mix proportions are listed in table [1].

Table 1: The optimal proportions of the SIFCON mixture

Cement (kg/m^3)	898.2
Sand (kg/m^3)	998
Silica fume (kg/m^3) 10% rep.	99.8
Steel fibers (%)	6,8, and 10
w/b* ratio	0.3
SP (by wt. of cement) %	3.7

*w/b= water/binder= water/ (cement+silica fume)

The compressive strength (fc) and split tensile strength (ft) tests were performed at 28 days in accordance with ASTM C39 [17] and ASTM C496-04 [18], respectively, using 100 mm diameter and 200 mm height cylinders.

Prisms of (100 mm width X 100 mm length X 500 mm depth) were used to determine the flexural strength (fr) in accordance with ASTM C-78 [19]. While the modulus of elasticity was determined by utilizing (150 mm diameter X 300 mm height) cylinders according to ASTM C469-02 [20]. Both the flexural strength and the modulus of elasticity are tested at 28 days of water curing. Figure [2] shows the crack patterns of the cylinders and prisms, and the mechanical properties of the SIFCON mix are tabulated in table [2].

Figure 2: Failure patterns of cylinders and prisms. a) compressive fracture pattern, b) splitting tensile fracture pattern, c) prism failure pattern

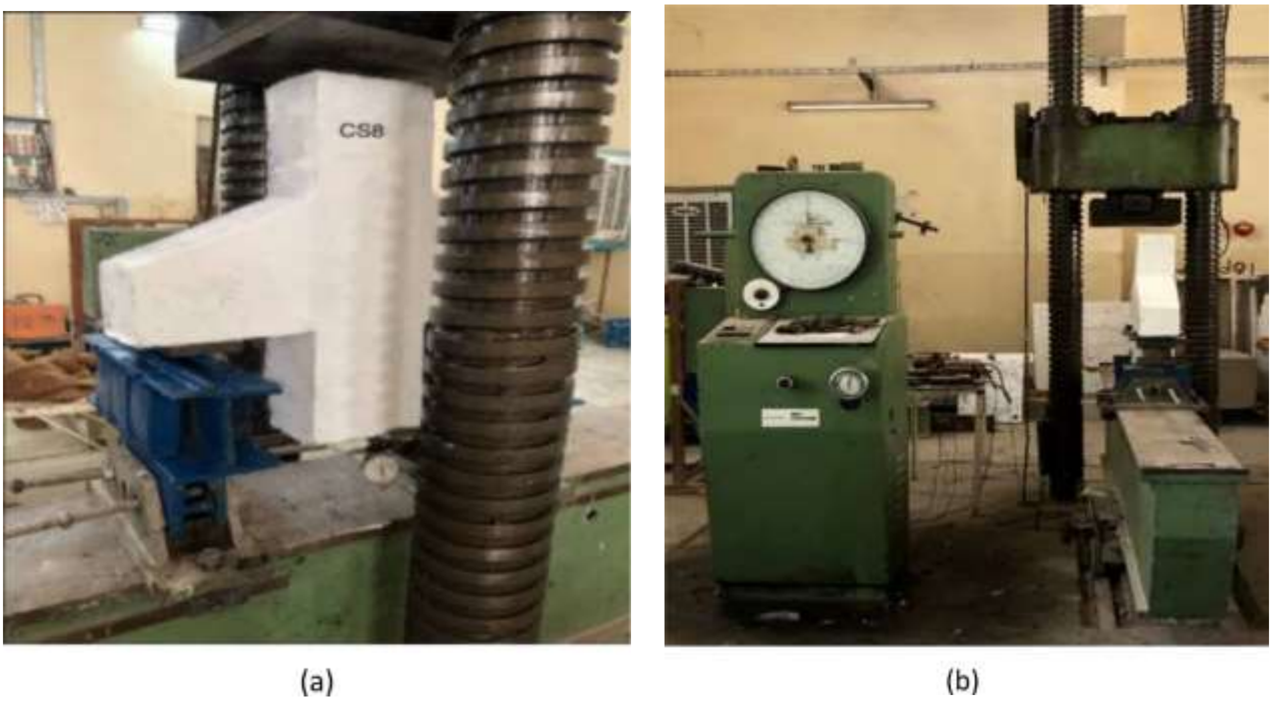
Table 2: Mechanical properties of SIFCON mix

Compressive strength* f_c' (MPa)	126
Split tensile strength f_t (MPa)	12.25
Flexural strength f_r (MPa)	22.125
Modulus of elasticity E_c (MPa)	47.8

* Compressive strength result is average of two values

TEST SET-UP AND INSTRUMENTATION

All of the SIFCON corbel specimens have been tasted in an inverted position in the Universal Hydraulic Testing Machine with a 3000 kN capacity at 28 days of curing in water. One mechanical dial gauge was used to measure the deflection at the center of the column. The readings of the deflection were recoded with each load increment until the failure occurred. Figure [3] demonstrates the setup of the specimen in the testing machine.



(a) (b)

Figure 3: Test set up. a) Set up of corbel specimen, b) Testing machine

RESULTS AND DISCUSSION

The values of the ultimate load, cracking load, failure mode, deflection corresponding to the ultimate load, and the variables handled in this study are listed in table [3]. C refers to corbel, S is referred to steel fiber, R is noted to steel reinforcement, while the number 6 refers to steel fiber content, and the numbers 1 and 3 refer to the value of shear span to effective depth ratio.

Table 3: Experimental results of SIFCON corbels

Corbel name	CS6-1	CS6-3	CS6R-1	CS6R-3
a/d	0.35	1.0	0.35	1.0
P_{cr} (kN)	137.5	95	155	130
P_u (kN)	770	400	797.5	507.5
Δ_u (mm)	2.45	2.64	2.4	2.43
Steel reinforce-ment	--	--	3Ø12 mm	3Ø12 mm
Failure mode	DS*	F**	F	F

**F: Flexural failure

*DS: Diagonal splitting failure

GENERERAL BEHAVIOR OF SIFCON CORBELS

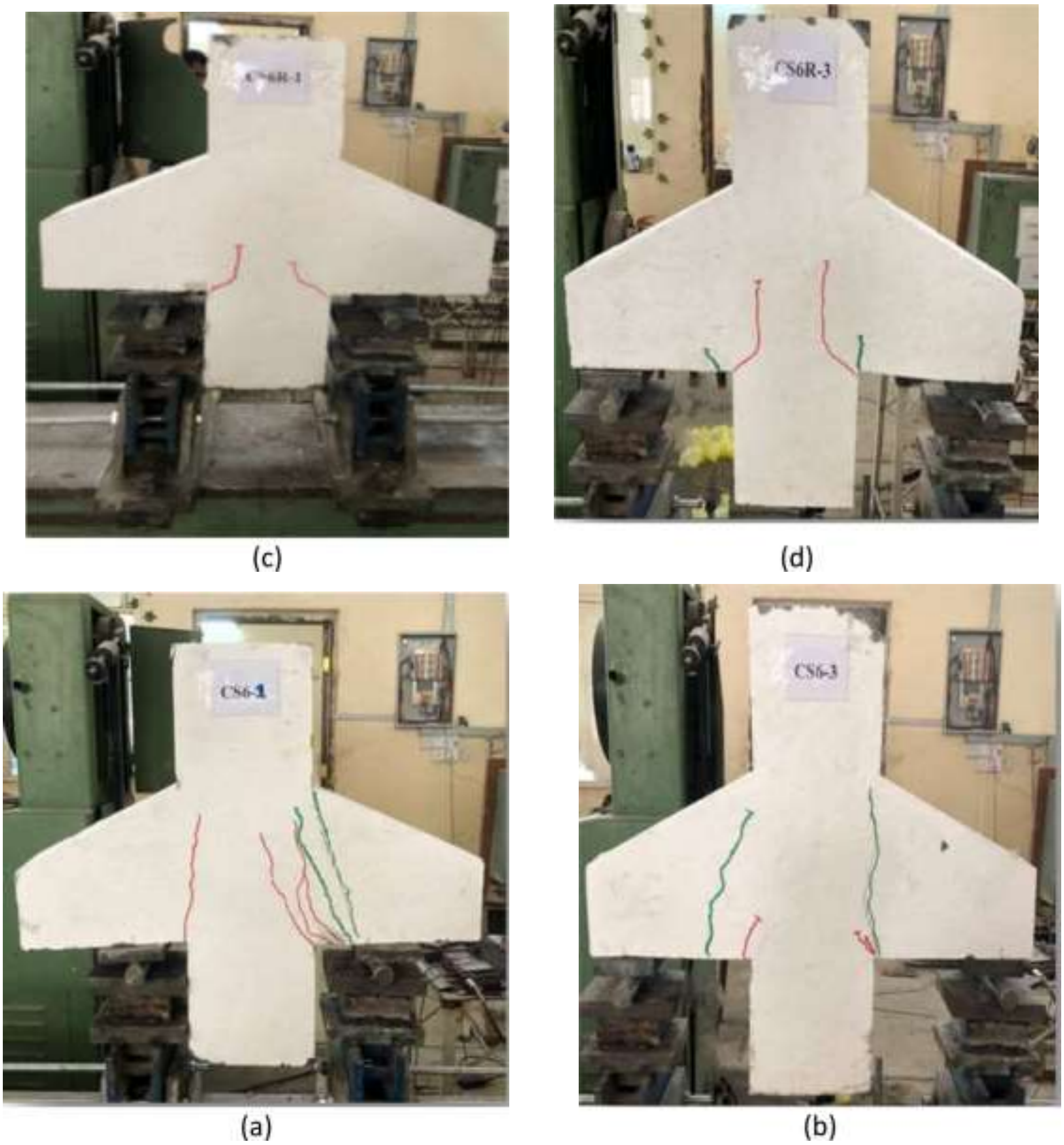
Firstly, when the SIFCON corbels were first loaded, they were entirely free of cracks. The first fractures appeared when flexural cracks appeared close to or at the intersection of the corbel tension face and the face of the column, propagating slowly along the column face or between the bearing plate and the column inside the corbel until the second main crack appeared.

Although the initial cracks grew and created the failure mode as indicated in figure [4], the failure was gradual due to the presence of steel fibers in corbels CS6R-1 and CS6R-3.

The early cracks combined to generate the second main crack, which caused the failure of corbel CS6-3, as seen in figure [4].

Further flexural fractures developed and additional flexural cracks formed in the shearing spans between the load and the support as the load increased, curving toward the loading areas.

The major fracture expanded toward the column-corbel intersection at the sloping edge of the corbel at greater load application levels. The failure mode is represented by this crack, which is referred to as the "major crack". All of the above-mentioned crack forms were noticed in corbel CS6-1, as shown in figure [4].



(c) (d)

(a) (b)

Figure 4: Crack patterns of SIFCON corbels. a) corbel CS6-1, b) corbel CS6-3, c) corbel CS6R-1, and d) corbel CS6R-3

FAILURE MODE

An increase in deflection with a decrease in applied load can be explained as a failure. The diagonal splitting failure appeared in corbel CS6-1, which may lead to shear failure because this type of crack formed after the splitting of the concrete. Another form of failure was noticed on corbel CS6-3. It was a flexural tension failure. This type of failure is formed at the intersection line between the column and the corbel and occurs after the pulling out of the fibers from the concrete matrix. The cracks in this failure mode are deep and wide opening and propagate vertically.

On the other hand, the flexural compression failure has taken place in both corbels CS6R-1 and CS6R-3, where the fibers are pulled out from the concrete matrix and the steel bars extensively yielded after the formation of the cracks, which are fewer in number with small openings compared to the two other corbels CS6-1 and CS6-3.

LOAD-DEFLECTION RESPONSE

The structural behavior of the tested specimens under loading is clarified by the load-deflection curve. One dial gauge with a precision of 0.01 mm was employed in this study.

The load-deflection curves in figure [5] represent the influence of the shearing span to effective depth (a/d) ratio. For all SIFCON corbels, the deflection values increase as (a/d) increases due to the increase in the bending moment, as seen in the graph.

At a specific load amount of 250 kN, the deflections of CS6-1 (a/d = 0.35), and CS6-3 (a/d = 1), are 1.1 mm, and 1.88 mm, respectively. When comparing the current results in this study with the earlier published work [21], when (a/d = 0.7) the defection value was 1.75 mm at the same load level and the same fractional volume of steel fibers (V_f = 6%) and the same geometry of the SIFCON corbel, that confirms the negative effect of (a/d) on the deflection of the SIFCON corbels.

In the SIFCON specimens that included main reinforcement bars CS6R-1 and CS6R-3, the deflection values increased from 1.0 mm to 1.55 mm at a magnitude of a load equal to 250 kN with an increase in (a/d) ratio from 0.35 to 1.

The use of steel bars had a positive influence on deflection values. From the start of load application and at the same value of (a/d), the deflection of corbels CS6R-1 and CS6R-3 is less than the deflection of the SIFCON corbels CS6-1 and CS6-3, respectively. The rationale for this action is that adding the main reinforcing bars increases the tensile strength of the corbels, resulting in lower deflection values.

At a 300 kN load level and (a/d = 0.35), the deflection of CS6-1 and CS6R-1 is around 1.23 mm and 1.1 mm, respectively, and 2.1 mm and 1.67 mm for corbels with (a/d = 1), CS6-3 and CS6R-3, respectively, at the same load level as clarified in figure [5].

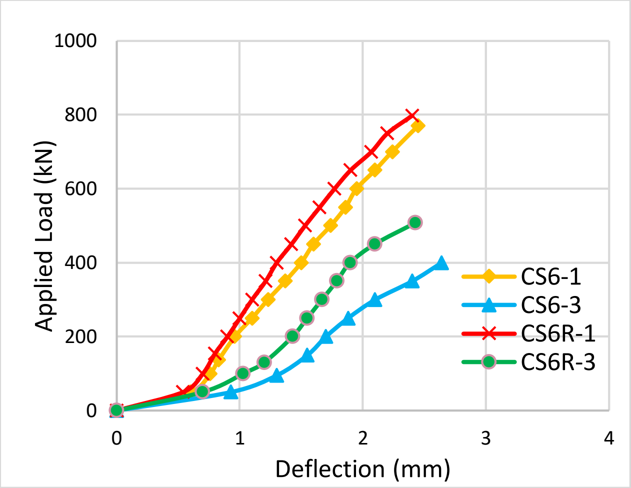


Figure 5: Effect of (a/d) on load-deflection curve of SIFCON corbels

ULTIMATE LOAD AND CRACKING LOAD

The shear span to effective depth ratio has a negative effect on both the ultimate load and the cracking load due to the decrease in bending moment. As the (a/d) ratio increased from 0.35 in corbel CS6-1 to 1.0 in corbel CS6-3, the value of the ultimate load and cracking load significantly decreased by about 48.05% and 30.91%, respectively. Comparing the results of the corbel CS6-1 in the current investigation with the corbel CS6 of (a/d = 0.7) from the previous study [21], the cracking load and the ultimate load decreased by about 18.18% and 44.16%, respectively, when the (a/d) ratio changed from 0.35 to 0.7, and by about 15.56% and 6.98%, respectively, when the (a/d) ratio changed from 0.7 to 1.0.

The same observations were recorded in the SIFCON corbels reinforced with main steel bars. When the shear span to effective depth ratio (a/d) increased from 0.35 in corbel CS6R-1 to 1.0 in corbel CS6R-3, a decrease of about 36.36% and 16.13% was noted for both ultimate load and cracking load, respectively. The effect of (a/d) on both ultimate load and cracking load is shown in figures [6] and [7], respectively.

On the other hand, the ultimate load and cracking load values of SIFCON corbels are enhanced with the addition of steel bars. In comparison to the CS6-1 and CS6-3 corbels, (a/d =0.35) and (a/d =1), respectively, an increase in ultimate load of roughly 3.57% and 26.875%, respectively, as well as an improvement in cracking load of around 12.73% and 36.84%, respectively, was noticed. Parallel fibers have around 30% more toughness than perpendicular fibers, which have little tensile strength or crack propagation resistance [22]. As a result, the random distribution of steel fibers may reduce SIFCON corbels' ability to underestimate applied loads, while the inclusion of steel bars increases the ultimate load more than SIFCON corbels. Figures [4] and [5] demonstrate the influence of using main reinforcement on the ultimate load and cracking load, respectively.

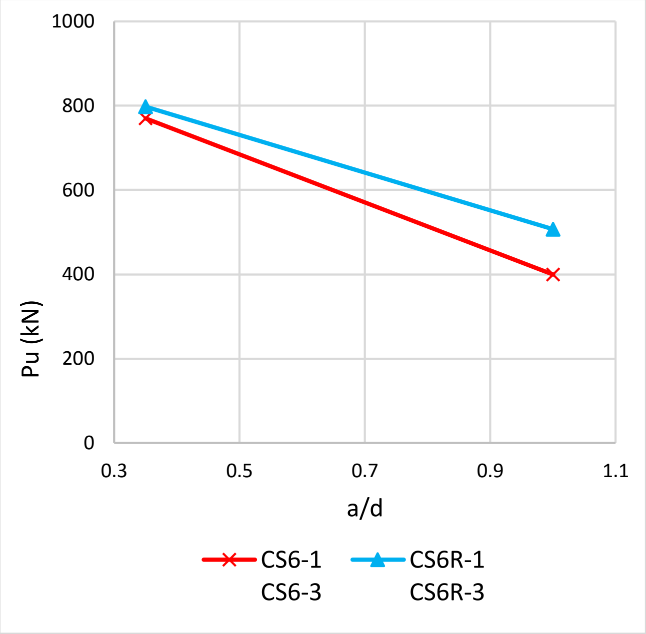


Figure 6: Effect of (a/d) and main steel bars on ultimate load of SIFCON corbels

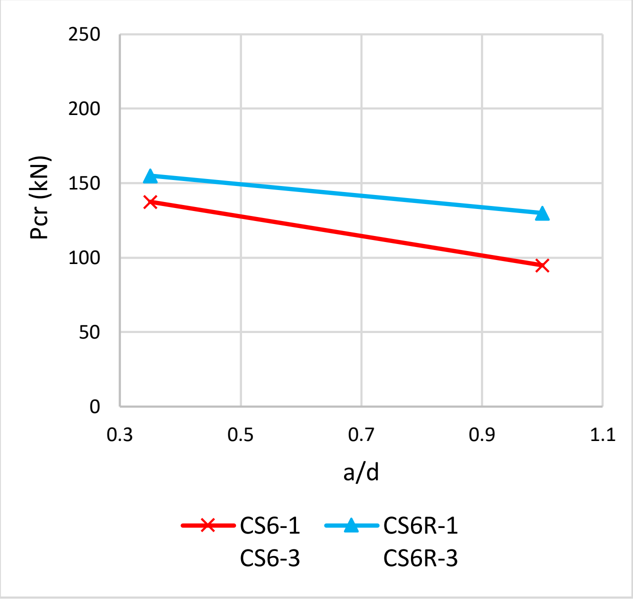


Figure 7: Effect of (a/d) and main steel bars on cracking load of SIFCON corbels

CONCLUSIONS

Based on the obtained experimental results, several conclusions are found and listed below:

1. The use of main steel bars and the changeable shear span/effective depth ratio have resulted in changing the failure mode of the SIFCON corbels.
2. In general, SIFCON has remarkable crack resistance due to the high content of steel fibers, which are responsible for the crack-bridging mechanism and crack-arresting mechanism that lead to delay the formation of the first crack and prevent the sudden failure.
3. The presence of steel bars improves the cracking load and ultimate load by about 12.73% and 3.57%, respectively, when (a/d = 0.35) and 36.84% and 26.875%, respectively, when (a/d = 1).
4. Due to the ability of SIFCON to enhance the failure mode and prevent the catastrophic shear cracks as well as the sudden shear mode, the transversal shear reinforcement can be eliminated.
5. The amount of deflection of SIFCON corbels increases as the shear span to effective depth ratio increases.
6. The deflection values of the SIFCON corbels with steel bars are less than the deflection of SIFCON corbels with the same amount of steel fiber volumetric ratio V_f.
7. The ultimate load and the cracking load decreased with the increase of the shear span to depth ratio (a/d) value from 0.35 to 1.0.

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