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Experimental Study of Reinforced Concrete Double Corbels Containing Steel Fibers Subjected to Eccentric Vertical Loads

Osama Mohamed*[1] ;gehan hamdy[1];Ayman Mohammed Ismail [2]

[1]Department of Civil Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt

[2] Housing and Building National Research Center (HBRC), Cairo, Egypt.

[*] Corresponding Author.

E-mail: osama.mohamed21@feng.bu.edu.eg; gehan.hamdy@feng.bu.edu.eg; ayman.m.ismail@gmail.com

Abstract: This research aims to investigate experimentally the torsional resistance of reinforced concrete (RC) double corbels and the effects of load eccentricity, variation of vertical, horizontal stirrups and corbel width. In the conducted experimental program, nine reinforced concrete (RC) double corbels containing fibers were cast and tested under centric and eccentric static vertical load until failure. Steel fibers have been added to the concrete mix to enhance concrete characteristics such as toughness, stiffness and strength, in addition to limiting micro crack propagation. The tested RC corbels had different widths and different amounts of vertical and horizontal stirrups. The experimental results studied are: (1) First crack load; (2) Maximum torque moment; (3) Twisting angle; (4) Displacement corresponding to the first crack load (5) Displacement corresponding to the failure moment; (6) Cracking pattern; (7) Displacement ductility; (8) Toughness; and (9) Failure mode. The experimental results showed that by increasing reinforcement of vertical stirrups and horizontal stirrups the ultimate torque of the tested specimens increased by 4.58% to 17.96% while increasing corbels width increased the ultimate torque by 24.32%. It can thus be concluded that the use of vertical and horizontal stirrups and increasing the corbel width caused noticeable improvement of the cracking and ultimate torque for RC corbels under eccentric vertical loads.

Keywords: Double corbels, Torsional failure, Twisting angle, Steel fibers.

1. INTRODUCTION

Corbels are brackets or short cantilevers with span to depth ratio (a/d) generally smaller than 1.0 used to support heavy concentrated loads or beam reactions. These members are common in bridges, industrial buildings with overhead cranes, precast structural systems and parking garages, and function to transfer vertical and horizontal loads to the main structural members. Many studies were conducted to determine experimentally, numerical and analytically the strength of such elements when subjected to vertical loads without eccentricity and investigate the different parameters that influence the performance of corbels [1, 2]. Addition of fibers in high-strength RC corbel increases the ductility and thus defines the mode of failure of the corbels, depending on the fiber parameters [2]. Abdel Hafez et al. [3] tested seventeen high-strength RC corbels with and without fibers having variable fiber content, shear span-to-depth ratio, concrete strength, area of main steel reinforcement and horizontal stirrups; results indicated that addition of steel fibers and horizontal stirrups improved the strength and ductility and showed to ductile behavior until failure. Salman et al. [4] tested ten self-compacting RC corbels with and without steel fibers subjected to concentric vertical loads, the variables were the shear span to effective depth ratio (a/d), the amount of steel fibers (Vf), and the concrete compressive strength. Results showed that addition of steel fibers by 0.4% increased the corbels cracking and ultimate loads by 31.5% and 25.3%, respectively; when the volume of steel fibers was 0.8% the cracking and ultimate loads increased by 41.1% and 29.1%, respectively, compared to nonfibrous corbels; also delay of cracking was observed for fibrous concrete corbels. Al-Shaarbaf et al. [5] tested 12 specimens of vibrated and self-compacting concrete (SCC) corbels under monotonic vertical loading until failure; results indicated that cracking and ultimate loads increased as a/d decreased and with increase in the number of horizontal stirrups; the use of SCC in corbels improved the behavior and increased the shear strength by 8.2% to 14.2%. Hamoodi et al. [6] tested eight RC corbels cast with or without recycled aggregate and showed that the presence of recycled aggregate slightly decreases the cracking and failure loads while reduction of a/d from 0.50 to 0.35 increases the crack and failure load by 8.1% and 20.2%, respectively, confirming that the corbel strength is much sensitive to decreasing a/d; the suitable ratio of recycled aggregate was recommended as 50%. Abdul-Alhassan and Jawad [7] tested nine steel fibrous RC and one plain RC specimens with f_{cu} 28.6 MPa under repeated vertical loads; results indicated the efficiency of using steel fibers 1.5% by volume of concrete and horizontal stirrups to obtain higher strength, deformation capacity and more ductile failure mode. Faleh et al. [8] investigated experimentally the shear behavior of 13 corbels of high-strength concrete (HSC) with steel fibers or with stirrups and showed that presence of fibers or closed stirrups enhanced the strength and decreased the deformation of the tested specimens and concluded that the horizontal shear reinforcement can be substituted by addition of steel fibers to HSC corbels. Saleh et al. [9] tested seven RC corbels, one specimen without fibers and six specimens had six types of fibers at a constant volume fraction 1% of the total concrete volume, the results indicated that steel fibers gave increase in the maximum load of 46.6% compared with polyolefin fibers, and that the shape of steel fiber clearly affects the ultimate load. Said et al. [10] studied experimentally the effect of hybrid fibers on the torsional behavior of RC beams; thirteen RC beams containing a mixture of three types of fibers: carbon, basalt and steel fibers were subjected to pure torsion until failure. The experimental results showed that the use of hybrid of steel and carbon fibers enhanced torsional moment, angle of twist, and energy absorption more than the other hybrids, while hybrid of basalt and steel fibers had a positive effect on ductility [10].

This research aims to study experimentally the torsional behavior of RC corbels containing steel fibers and explore the effect of several variables on the behavior such as the eccentricity of the vertical loads, vertical stirrups, horizontal stirrups and change of corbels width. An experimental program is conducted where RC double corbels containing steel fibers are subjected to torsion generated by eccentric vertical loads until failure. The experimental procedures are described, and the results are presented and discussed in the following sections.

2. EXPERIMENTAL PROGRAM

2.1. Test specimens

The experimental program conducted in the Reinforced Concrete Laboratory of the Faculty of Engineering at Cairo University consists of nine RC double corbels as listed in Table 1. The shape and concrete dimensions of the test specimens are shown in Figs. 1 and 2. In the control corbel DC1, the vertical load is applied with no eccentricity. In order to generate torsional moments in specimens DC2 to DC9 when vertical load is applied, cantilevers (arms) are made as shown in Figs. 1(b) and Fig. 2(b-d) with reinforcement 3 Ø12 and stirrups 7 Ø 8 @100 mm. The dimension from column to corbel end is equal to 500 mm. Corbels specimens D1 to D7 have width 300 mm; corbels DC8 and DC9 have corbel width 250 and 350 mm, respectively. The column has 700 mm clear height and a rectangular cross section of 300×400 mm for corbels DC1 to DC7, while for specimens DC8 and DC9 the column cross section is 250×400 mm and 350×400 mm, respectively.

Table 1. Dimensions and reinforcement of tested specimens

Specimen ID	Group Number	Width b (mm)	(e/b) (-)	Vertical Stirrups	Horizontal Stirrups
DC1	Control	300	0.00	2 ∅ 8	3 ∅ 8
DC1	I	300	0.00	2 ∅ 8	3 ∅ 8
DC2		300	0.50	2 ∅ 8	3 ∅ 8
DC3		300	0.75	2 ∅ 8	3 ∅ 8
DC3	II	300	0.75	2 ∅ 8	3 ∅ 8
DC4		300	0.75	3 ∅ 8	3 ∅ 8
DC5		300	0.75	4 ∅ 8	3 ∅ 8
DC3	III	300	0.75	2 ∅ 8	3 ∅ 8
DC6		300	0.75	2 ∅ 8	2 ∅ 8
DC7		300	0.75	2 ∅ 8	4 ∅ 8
DC3	IV	300	0.75	2 ∅ 8	3 ∅ 8
DC8		250	0.75	2 ∅ 8	3 ∅ 8
DC9		350	0.75	2 ∅ 8	3 ∅ 8

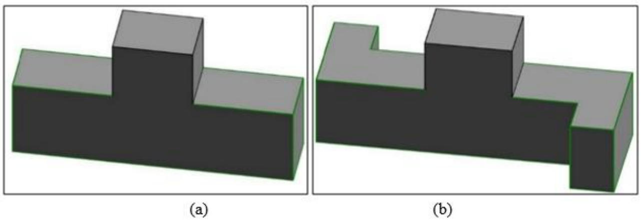


Fig 1. Shape of tested corbels: (a) control DC1 (b) DC2 to DC9

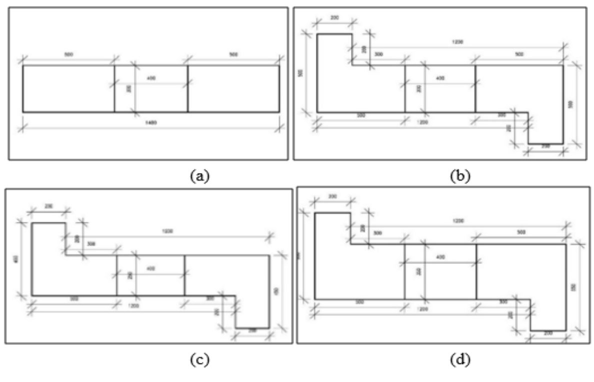


Fig 2. Concrete dimensions of (a) control DC1 (b) DC2,3,4,5,6,7, (c) DC8, and (d) DC9

All tested specimens have the same cantilever reinforcement 5Ø12, column heads have vertical reinforcement 8Ø16 and stirrups 7Ø8 @100 mm. Corbels DC1, DC2 & DC3 have vertical stirrups 2 Ø 8 @200 mm and horizontal stirrups 3 Ø 8 @84 mm, as given in Table 1 and shown in Fig. 3; while vertical stirrups are varied to be 3 Ø 8 @135 mm for DC4 and 4 Ø 8 @100 mm for DC5, as shown Fig. 4. Horizontal stirrups are 2 Ø 8 @125 mm for DC6 and 4 Ø 8 @63 mm for DC7. Specimens DC8 and DC9 have width 250 mm and 350 mm, respectively, and same reinforcement as DC1, DC2 and DC3. The cantilevers (arms) have reinforcement 3 Ø12 and stirrups 7 Ø 8 @100 mm.

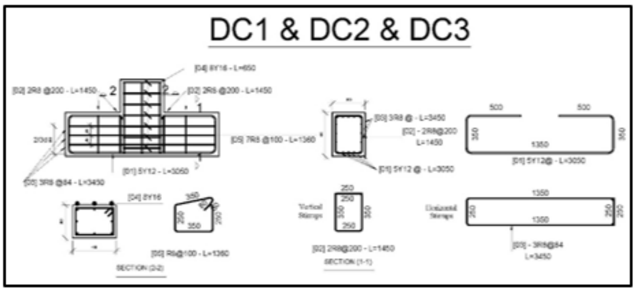


Fig 3. Reinforcement details of corbels DC1, DC2 and DC3

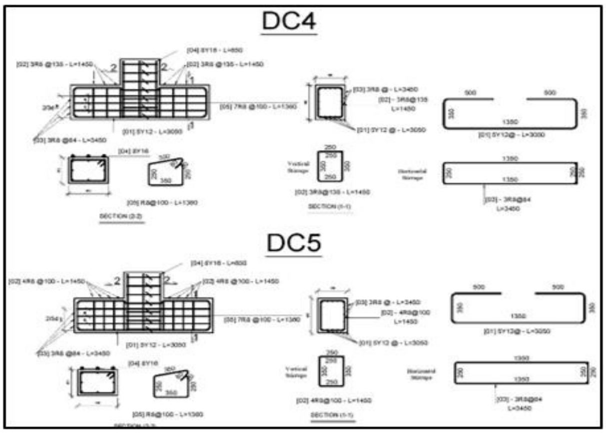


Fig 4. Reinforcement details of corbels DC4 and DC5

2.2. Materials, mix proportions and specimens preparation

The concrete mixture used in casting the test specimens was designed according to Egyptian codes ECP 208-2019 [11] and ASTM,17 [12] to achieve target 28-day cubic compressive strength of 30 MPa, Table 2 shows the weight of the mix constituents for one cubic meter of concrete.

The materials used for concrete mix include ordinary Portland cement (OPC), fine aggregates (sand), coarse aggregates (crushed stone), additive and water. Fine aggregate is clean sand while coarse aggregate used is dolomite crushed to size 10 and 20mm. Superplasticizer additive is used to reduce mixing water and thus improve workability and cohesion of the concrete mix; Sikament-R4PN suitable for tropical and climatic conditions is used in this research. High tensile steel (40/60) having proof strength 400 MPa is used as main reinforcement of corbels, columns and arms. Mild tensile steel (24/37) having 240 MPa yield stress is used for stirrups. Steel fibers are added to the concrete mix in order to improve the hardened concrete mechanical properties and enhance its resistance to macro-microcracks. The steel fibers shape and properties are given in Fig. 5 and Table 3.

Table 3. Properties of steel fibers

Length (L)	35 mm (+/- 3 mm)
Diameter (D)	0.80 mm (+/- 0.05 mm)
Aspect ratio (L/D)	43.75
Middle length (ML)	40 mm (+/- 3 mm)
Height of hook (HH)	2.10 - 2.90 mm
Length of hook (HL)	4 - 6 mm
Tensile Strength	1000 N/mm^2

Table 2. Mix proportions of concrete

Material	Cement	Fine agg. (sand)	Coarse agg. (10 mm)	Coarse agg. (20 mm)	Super-plasticizer	Steel fibers	Water
Weight (kg/m^3)	400	692	526	565	3	35	200

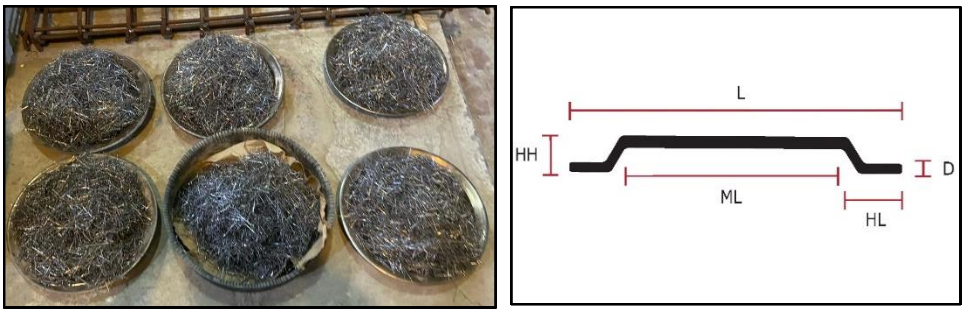


Fig 5. Steel fibers

Table 4. Properties of reinforcement steel

Type	Bar diameter (mm)	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	Max. elongation (%)
Mild steel	8	378	429.43	26
High strength steel	12	565	656.72	20
	16	542	657.81	22.5

Fig 6. Reinforcement cage for RC corbels DC1, DC2 and DC3

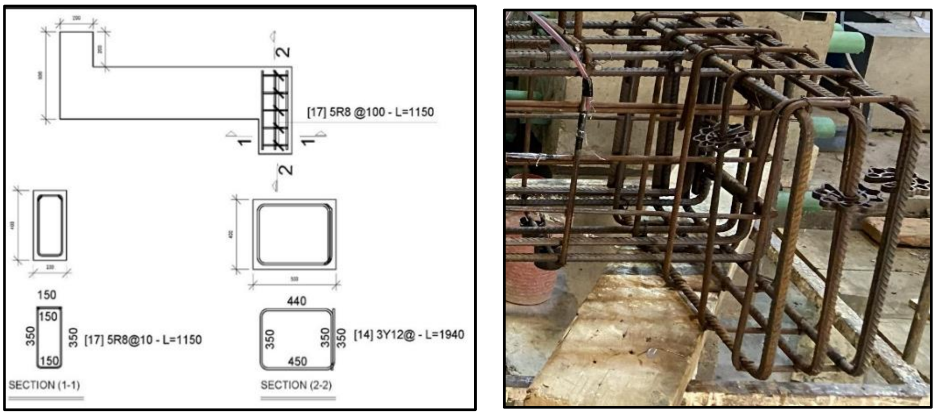


Fig 7. Reinforcement of corbels arms

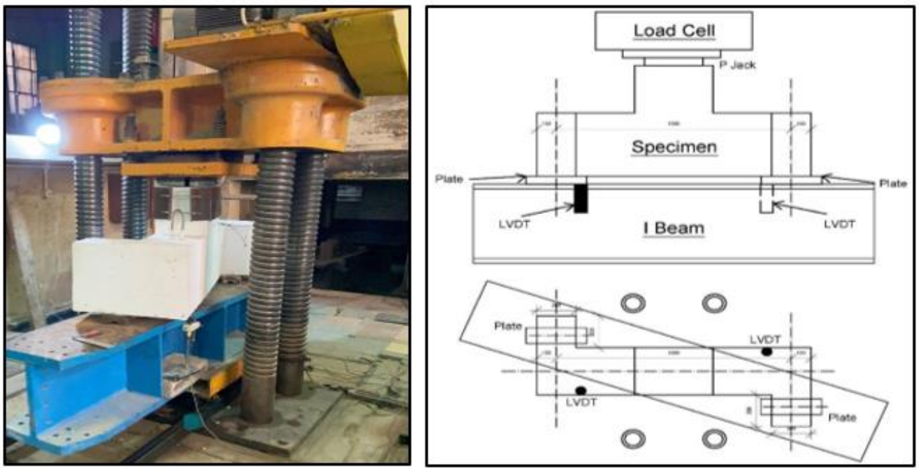


Fig 8. Test setup

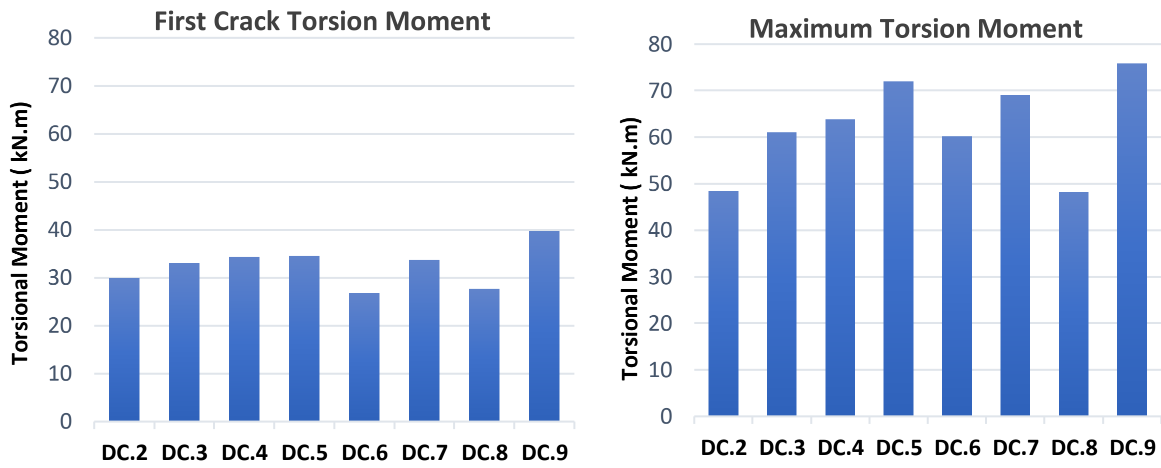
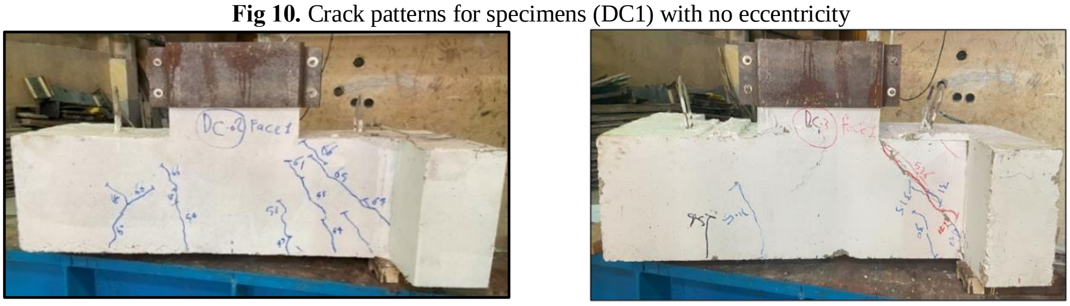


Fig 9. First crack moment and maximum torsional moment

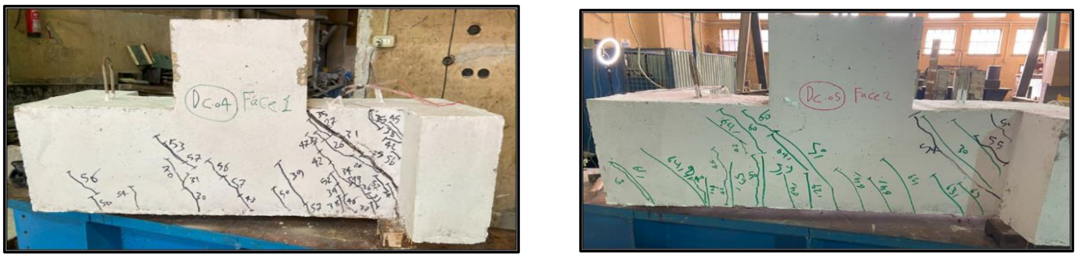
Table 5. Experimental results

Specimen	First Crack				Ultimate			
	Tcr (kNm)	**Tcr /T_{crDC3}**	**θcr (deg/m)**	**θcr /$θ_{crDC3}$**	**Tu (kNm)**	**Tu /T_{uDC3}**	**θu (deg/m)**	**θu /$θ_{uDC3}$**
DC.1	No torsion				No torsion			
DC.2	29.79	90%	0.01	42%	48.40	79%	0.033	51%
DC.3	32.99	-	0.024	-	60.98	-	0.065	-
DC.4	34.31	104%	0.015	63%	63.77	105%	0.09	138%
DC.5	34.53	105%	0.029	121%	71.93	118%	0.11	169%
DC.6	26.70	81%	0.008	33%	60.13	99%	0.07	108%
DC.7	33.65	102%	0.034	142%	69.06	113%	0.13	200%
DC.8	27.67	84%	0.026	108%	48.18	79%	0.10	154%
DC.9	39.64	120%	0.015	63%	75.81	124%	0.07	108%

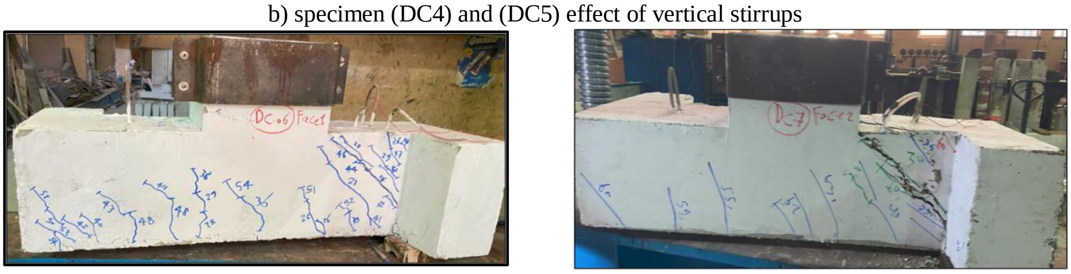
Fig 10. Crack patterns for specimens (DC1) with no eccentricity



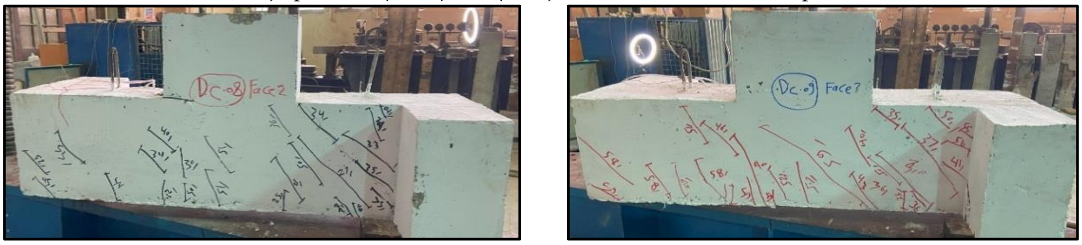
a) specimens (DC2) and (DC3) effect of load eccentricity



b) specimen (DC4) and (DC5) effect of vertical stirrups



c) specimen (DC.6) and (DC7) effect of horizontal stirrups



d) specimen (DC.8) and (DC9) effect of corbel width

Fig 11. Crack patterns for specimens (DC2 to (DC9)

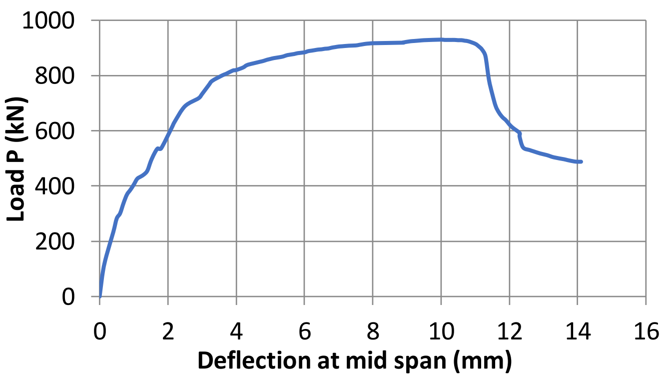


Fig 12. Load-deflection relation for control corbel DC.1

The concrete materials were weighed according to the mix design. Sand, dolomite, cement and steel fibers were dry mixed using a concrete tilting drum mixer for about one minute until a homogenous color was observed by. After that, water and superplasticizer were added gradually while mixing for a further two minutes.

Concrete cubes and cylinders were cast to be experimentally tested after 28 days in compression to evaluate the compressive and splitting tensile strengths according to Egyptian code ECP 208-2019 [11]; the average cubic and cylindrical concrete compressive strengths were 39.26 and 31.5 MPa, respectively, while the average tensile strength was 3.67 MPa. Also, samples of steel bars with diameter 8,12 and 16 mm were tested in tension; the obtained values are given in Table 4. Molds for casting the RC corbels and steel reinforcement were prepared as shown in Figs. 6 and 7. Concrete were cast in the molds and cured for 28 days until the tests were performed.

2.2. Test setup and testing procedure

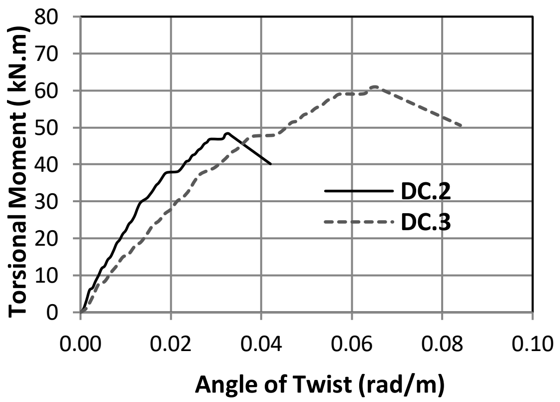
The tested corbels were subjected to torsional moment by applying vertical load on the column through load cell with capacity 5000 kN. the test setup is shown in Fig. 8. Two LVDTs were positioned at ends of the specimen to measure the vertical movements of the bottom fiber at the opposite corners of the specimen end. The tested specimens were colored by white paint to facilitate detection of cracks. To record the deflection, twisting angle and vertical load, external measuring devices (linear variable differential transducer (LVDT) and load cell) are connected to data logger. A hydraulic actuator is used to apply the load in increments until failure. Deflections, angle of twist, first cracking loads and ultimate failure loads are recorded; propagation of cracks are marked.

3.EXPERIMENTAL RESULTS

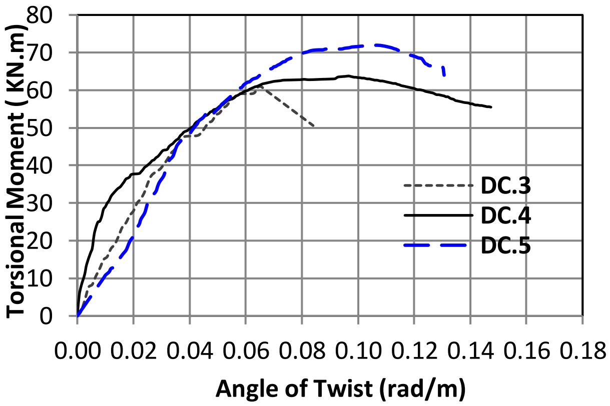
For the control specimen, DC.1 without eccentricity, the cracking and maximum loads were equal to 300 kN and the 930 kN, respectively. For the specimens with eccentricity, the first crack and ultimate torsional moments are calculated from the recorded loads and are plotted in Fig. 9. The difference between the vertical movements of the bottom fiber at the opposite corners measured by LVDTs is used to calculate the twisting angle. Table 5 lists the torsional moments and angles of twist at the cracking and final stages for all tested specimens, additionally the values are compared to those of specimen DC3. The crack patterns on the front and back of all specimens are shown in Figs.10 and 11. The relation between the applied load and deflection for the control corbel (DC.1) tested under vertical load are plotted in Fig.12. For the corbels tested under eccentric load, the relations between the applied twisting moment and the recorded twisting angle are plotted in Fig. 13.

3.1. Effect of eccentricity of load

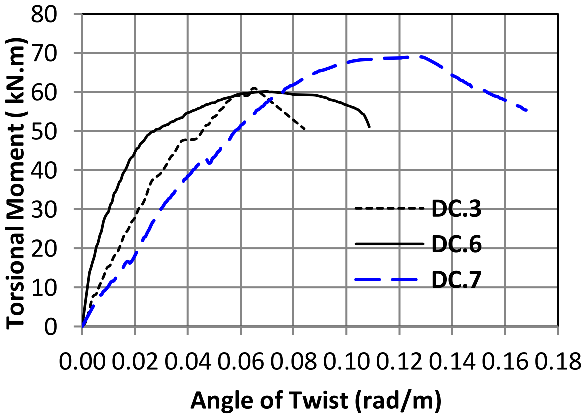
Comparing the results given in Table 5 for specimens DC.2 and DC.3 having eccentricity (e/b) 0.5 and 0.75, respectively, it is observed that due to decreasing the eccentricity of specimen DC.2, the cracking torque, T_{cr}, and the ultimate torque, T_u, decreased by 10.7% and 26%, respectively. To illustrate the effect of eccentricity of load, the torsional moment - angle of twist relationship for specimens of specimens (DC.2) and (DC.3) are plotted in Fig. 13(a). Specimens (DC.2) and (DC.3) show similar behavior; the first stage of the curves is linear up to the cracking torsion while the second stage shows nonlinear behavior, and the rotation angle increases with increasing the torsional moment indicating the post-cracking behavior. Compared to specimen (DC.3), the torsional moment capacity of specimen (DC.2) with eccentricity (e/b) equal to 0.5 decreased by 26%, while the maximum angle of twist decreased by 97%.



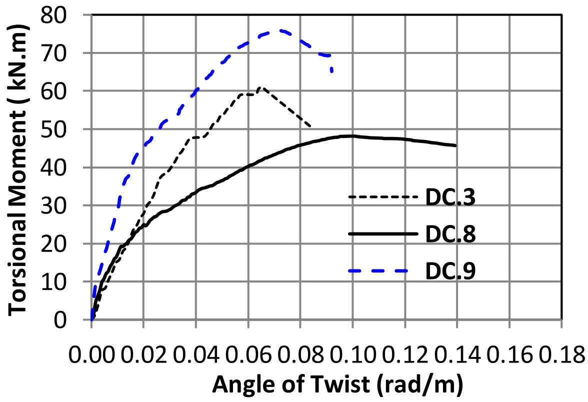
(a) group I specimens



(b) group II specimens



(c) group III specimens



(d) group IV specimens

Fig 13. Torsional moment -angle of twist relations for tested specimens

3.2. Effect of vertical stirrups

It is observed from the results given in Table 5 that increasing the vertical stirrups from 2 Ø 8 in specimen DC3 to be 3 Ø 8 in DC.4 and 4 Ø 8 in DC.5 led to increase of the cracking torque T_{cr} by 4% and 4.7%, and of the ultimate torque T_u by 4.6% and 18%, respectively. To illustrate the effect of increasing the vertical stirrups, the torsional moment - angle of twist relationship for specimens (DC.4) and (DC.5) are plotted in Fig. 13(b) compared to that of specimen (DC.3). The results show increase of torsional moment of (DC.4) and (DC.5) by 4.6% and 18% while the maximum angle of twist increased by 38.5% and 69.2%, respectively, compared to (DC.3).

3.3. Effect of horizontal stirrups

As the horizontal stirrups decreased from 3 Ø 8 to 2 Ø 8 in specimen DC.6, T_{cr} and T_u decreased by 23.6% and 1.4%, respectively. For specimen DC.7, the horizontal stirrups were increased to 4 Ø 8, T_{cr} and T_u increased by 2% and 13.3%, respectively, compared to DC.3 with 4 Ø 8 horizontal stirrups. The torsional moment - angle of twist relationships for the specimens of group III are compared with that of specimen (DC.3) in Fig. 13(c). It is noticed that the first stage of the curves is linear up to the cracking torsion, the second stage of the curves are nonlinear where the rotation angle increases with increasing the torsional moment indicating the post-cracking behavior. Compared with specimen (DC.3), the maximum angle of twist for increased by 7.1% for specimen (DC.6) and increased by 100%, for specimen (DC.7).

3.4. Effect of corbel width

The experimental results listed in Table 5 indicate that the cracking load, T_{cr}, and the ultimate load, T_u, decreased with decreasing the corbel width to 250 mm in specimen DC.8. by 19.2% and 26.6%, respectively, compared to DC.3 having 300 mm width. As the corbel width was increased to be 350 mm in DC.9, T_{cr} and T_u increased by 20.2% and 24.3%, respectively, compared to DC.3 having 300mm with. The relations between the torsional moment and angle of twist for group IV specimens (DC.8 and DC.9 compared to DC.3) are plotted in Fig. 13(d). It is noted that the first stage of the curves was linear up to the cracking torsion, the behavior of specimen (DC.3) similar to the specimen (DC.8) and (DC.9). Compared to specimen (DC.3), the ultimate torsional moment for specimen (DC.8) decreased by 26.6% and the maximum angle of twist increased by 53.8%, while for specimen DC.9, the torsional moment increased by 24.3% and the maximum angle of twist increased by 7.1%.

3.5. Cracking behavior and failure mode

From the experimental work and observations regarding crack configuration shown in Fig.11, all the tested specimens failed in torsion except specimen (DC.1) without eccentricity that failed in shear. For specimen (DC.1), the first cracks appeared were diagonal cracks inclined at angle of 45º with the longitudinal axis of the specimen. With increasing the load, diagonal cracks spread out to right and left of column, additional appeared small cracks at mid span and the mode of failure was a shear failure as shown in Fig. 10. For specimens with eccentricity, the failure was indicated by a significant decrease in the applied load and a considerable increase in the specimens' angles of twist. The first cracks were diagonal inclined angle of 45º with the longitudinal axis of the specimen; by increasing the load, diagonal cracks run roughly parallel throughout the length of the member, additional small cracks appeared at mid span and the mode of failure was a torsion failure as shown in Fig. 11. In group II with variable vertical stirrups, group III with variable horizontal stirrups and group IV where corbel width was varied, the number of diagonal cracks spread out to right and left of the column and were greater in number than in specimen (DC.3), The number of cracks increased with increasing the amount of reinforcement vertical stirrups and horizontal stirrups in addition to increasing the corbel's width.

3. CONCLUSIONS

This research presented experimental investigation of the performance of reinforced concrete double corbels under eccentric vertical loads. Based on the experimental findings of this study, the main conclusions for the range of studied parameters may be outlined in the following points.

- Diagonal cracks were spread out to perform a spiral trajectory inclined by 45º with the longitudinal axis of the tested specimens on the elevations, sides and top with increasing the applied torque.
- The ultimate load for corbel without eccentricity surpassed that for specimens with eccentricity.
- Decreasing eccentricity from 0.75 (a/d) to 0.5 (a/d), the cracking and ultimate torque decreased by 10.7% and 26%, respectively
- Increasing the number of vertical stirrups from 2 Ø 8 to 3 Ø 8, the cracking and ultimate torque increased by 4% and 4.6%, respectively. Increasing the vertical stirrups from 2 Ø 8 to 4 Ø 8, the cracking and ultimate torque increased by 4.7% and 18%, respectively.
- Decreasing the horizontal stirrups from3 Ø 8 to 2 Ø 8, the cracking and ultimate torque decreased by 23.6% and 1.4%, respectively. Increasing the horizontal stirrups from 3 Ø 8 to 4 Ø 8, the cracking and ultimate torque increased by 2% and 13.3%, respectively.

- Decreasing corbel width from 300 mm to 250 mm, the cracking and ultimate torque decreased by 19.2% and 26.6%, respectively. Increasing corbel width from 300 mm to 350 mm, the cracking and the ultimate torque increased by 20.2% and 24.3%, respectively.
- Increasing reinforcement of vertical and horizontal stirrups and the corbel width caused noticeable improvement of the cracking and ultimate torque for the tested specimens. Increasing reinforcement of vertical and horizontal stirrups and the corbel width increased the number and spread of inclined cracks.

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