1. INTRODUCTION

Corbels are structural members very commonly used in reinforced concrete structures and particularly in precast structures where their principal function is the transfer of vertical and horizontal forces to principal members. Corbels are structural members characterized by a shear span-depth ratio (a/d) generally lower than unity and subjected to concentrated forces as in the support zones. Earlier investigations with regard to the properties of concrete corbels reinforced with steel fibers (Fattuhi and Hughes 1989; Fattuhi 1990a, 1990b, 1994) demonstrated that to increase the strength and improve the ductility of corbels, it is necessary to increase the percentages of transverse steel (generally constituted by horizontal stirrups or inclined bars) or partially substitute the secondary shear steel reinforcements by using fiber reinforced concrete. Hence, the use of fibers will eliminate the need for complex reinforcement which is required whenever stirrups are used. These studies also stress the use of fibers in producing significant increases in the tensile properties and ductility of corbels. In addition, many studies in the literature (Kumar 2004; Campione et al. 2005; Campione et al. 2007; Campione 2009; Yang et al. 2012) are addressed to experimentally and analytically determine the strength of such elements to highlight the role of the parameters that
influence the performance of corbels including shape and dimension of corbels, type of main and secondary steel reinforcements, presence and type of fibers, and strength of concrete. However numerous studies have been conducted to determine the behavior of fiber reinforced concrete corbels. Limited studies have been reported in the published literature on the shear behavior and strength of carbon fiber reinforced concrete corbels (Al-Zahawi, 2011). This paper aims to experimentally investigate the shear behavior of concrete corbels reinforced with chopped carbon fiber or stirrups. Hence, this study provides additional data useful in the development of more general design criteria for determining the strength of carbon fiber reinforced concrete corbels subjected to vertical loading only.

2. EXPERIMENTAL INVESTIGATION

A typical test specimen consisted of a double-sided corbel integrated with a short vertical column, as shown in Figure 1. The corbel segment had a width of 120 mm and a total depth of 250 mm. All corbels were reinforced with three 12 mm deformed main longitudinal steel bars located at an effective depth of 220 mm from the compression face of the corbel. Two 12 mm diameter cross bars were welded to the main bars close to the free end of each corbel to avoid bond failure as proposed in ACI 318-14. The column segment was reinforced with four 12 mm deformed longitudinal steel bars and 6 mm deformed bars as closed ties placed at a spacing of 150 mm. The deformed bars of 6 mm were also used for shear reinforcement in the corbels and as framing bars to support the stirrups. Shear span-to-effective depth ratio (a/d) equal to 0.591 for all corbel specimens.

The test matrix is given in Table 1. A total of 10 specimens were constructed and tested. The specimens were divided into two main groups based on type of their concrete compressive strength. Specimens of Group A were constructed to obtain a cylinder compressive strength of 35 MPa at 28 days, whereas specimens of Group B supposed to have a cylinder compressive strength of 50 MPa at 28 days. All corbels were reinforced with same main reinforcement. In each group, one specimen did not include shear reinforcement to act as a control. The remaining specimens were reinforced with either stirrups or chopped carbon fibers. Within each group, the volume fraction of the carbon fibers and number of stirrups were varied. The used 12 and 6 mm diameter deformed steel bars had measured yield strengths of 490 and 500 MPa, respectively. Chopped carbon fiber brought form Qidong Carbon Material factory in China as filaments was used in this investigation. The fibers had an average length of 20 mm, a diameter of 7-8 μm, a tensile strength of 2840 MPa, a Young’s modulus of 235 GPa, and a density of 1.78 gm/cm3.

A high range water reducing admixture (PC175) was used to produce the concrete mix. Densified silica fume was used as recommended by ACI committee 544 instructions (2002). Portland cement type I (P. C. type I) was used. The maximum size of coarse aggregate was 9.52 mm. A normal and moderately high strength concrete were used. Matrix I designated with mix proportions of (1:1.19:1.8) by weight, w/c of 0.45, admixture of 0.5% by weight of cement, and silica fume 10% as replacement by weight of cement. This can produce a cylinder compressive strength of approximately 35 MPa at 28 day. For Matrix II, several trial mixes were carried out to determine silica fume content and dosage of superplasticizer in order to obtain a mix with the required compressive strength. Thus same proportions as Matrix I was used, but with w/c of 0.35, admixture of 1%, and silica fume of 15% as replacement by weight of cement which produce a cylinder compressive strength...
of 50 MPa at 28 day. Finally chopped carbon fiber with volume fractions of (0.2% and 0.4%) were added to the selected concrete mixes.

Mixing of carbon fiber concrete raised a number of problems because of the small diameter and short length of the fiber filaments. After the water, aggregate and cement have been fully mixed, fibers were slowly added to the concrete by hand spraying, while the mixer was rotating. Before placing concrete in the corbel mold, the reinforcement cage was positioned in the mold. Companion 100 mm cubes were cast and cured along with the corbel specimens. A testing machine with a bearing capacity of 2500 kN was used to perform the corbels tests at age of 56 days. The deflection under the column segment was measured by using a dialgauge with an accuracy of 0.01 mm and a search was made for the appearance of any cracks. The corbels were tested in an inverted position as shown in Figure 2. Tensile strains that occurred at the closed horizontal stirrups and at the main reinforcing bars were measured using precision pre-wired strain gauges of type (FLA-6-11-3L). The positions of steel strain gauges are shown in Figure 2.

Figure: Typical test Specimen (dimension are in mm)
Table 1: Details of test specimen

| Group No. | Specimen No. | $f_c$ (MPa) | Detail of Stirrups | $\rho_h f_{yh}$ (MPa) | $V_f$ (Fiber content %) |
|-----------|--------------|-------------|--------------------|------------------------|------------------------|
| A         | A1           |             | ----               | 0.0                    | 0.0                    |
| A         | A2           | 35          | 1-Ø6 mm            | 1.070                  | 0.0                    |
| A         | A3           |             | 2-Ø6 mm            | 2.141                  | 0.0                    |
| A         | A4           |             | ----               | 0.0                    | 0.2                    |
| A         | A5           |             | ----               | 0.0                    | 0.4                    |
| B         | B1           |             | ----               | 0.0                    | 0.0                    |
| B         | B2           |             | 1-Ø6 mm            | 1.070                  | 0.0                    |
| B         | B3           |             | 2-Ø6 mm            | 2.141                  | 0.0                    |
| B         | B4           |             | ----               | 0.0                    | 0.2                    |
| B         | B5           |             | ----               | 0.0                    | 0.4                    |

$\rho_h$: steel reinforcement ratio of horizontal shear stirrup

$f_{yh}$: specified yield strength of horizontal shear reinforcement
3. Experimental Results

In this section, the test results on corbels containing either carbon fibers or stirrups are presented. The results discussed though cracking load and corbels carrying capacities, crack patterns, load deflection curves, and steel strains. The test results including the first shear cracking and ultimate loads for different corbels are shown in Table 2.

3.1. Shear Strength of the tested Corbels:

3.1.1. Effect of Horizontal Shear Reinforcement Index

For the non-fibrous normal strength concrete corbels (Group A), the increase in the amount of $\rho_{h,f_{yh}}$ 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 $\rho_{h,f_{yh}}$ from 0 to 2.141 MPa caused an increase 29.6% and 14.5% respectively.

For the non-fibrous moderately high strength concrete corbels (Group B), the increase in the amount of $\rho_{h,f_{yh}}$ from 0 to 1.070 MPa caused an increase in the cracking and ultimate load of about 32.0% and 8.2% respectively. It was found that by increasing $\rho_{h,f_{yh}}$ from 0 to 2.141 MPa an increase was caused of about 45.6% and 18.2% respectively.

3.1.2. Effect of carbon fiber content

The result presented in Table 2 and Figure 3 indicate that the addition of carbon fibers for all corbels resulted in higher resistance against formation of the first crack. The first crack loads for non-fibrous concrete specimen were 81 kN and 103 kN for corbels with normal and moderately high strength concrete respectively.
The values increased 29.6% and 31.1% due to presence of 0.2% carbon fibers respectively. While 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 the corbel first shear cracking load can be significantly enhanced upon the addition of carbon fibers. Furthermore, it can be indicated that the presence of carbon fibers has slight effect on ultimate load capacity of tested corbels, as
compared with 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. The percentage increases in ultimate loads were 1.32% and 2.4% due to the presence of 0.2% carbon fibers respectively. Finally, the percentage increases in the ultimate loads were 6.6% and 9.3% due to the presence of carbon fibers at 0.4%. The results indicated that presence of carbon fibers slightly enhanced the corbel ultimate load. Effect of volume fraction of fibers on the ultimate load for corbels with various concrete grades is shown in Figure 4.

![Figure 4: Effect of carbon fiber content on ultimate loads](image)

### 3.1.3. Effect of Compressive strength of concrete

The test results presented in Table 2 indicated that the increase in compressive strength of tested corbels causes an increase in the cracking and ultimate loads of the tested corbels. The percentage increase in the ultimate loads were about 27.5% and 32.3%; while for cracking loads were more than 40% 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%.

#### 3.2. Crack patterns

The first cracks in all corbel specimens are flexural cracks, which appear at the corbel column interfaces, then propagated along the column-corbel interface. In addition, other cracks occurred near the inner edge of the bearing plate and propagated much faster than the first crack toward the junction of the column and the sloping face of the corbel. The second crack type, which now became the major cracks, eventually ran between the inner edge of the bearing plate and the column-corbel junction at the sloping face, and was responsible for the failure of the corbel. Failure was defined as the point at which the load could no longer be increased. Some minor secondary cracks also formed before failure. All specimens showed crushing of the concrete at the bottom of the sloping face of the corbel. The failure was stable and ductile for specimens with shear reinforcement. Reduce of the brittleness of the mechanism involving crushing of compressed regions has been indicated by using fibers instead of transverse stirrups improving the ductility significantly. It was observed that the addition of carbon fibers and the increase in the percentage of carbon fibers has effectively reduced the crack widths in the corbel specimens. Figure 5, shows the crack patterns for typical tested specimens.
3.3. Load deflection curves

Figures 6 and 7 show the load versus deflection curves for the corbel specimens. The shape of the load deflection curve at the post cracking stages varied according to the presence and absence of the horizontal shear reinforcement and volume fraction of fibers for specific grade of concrete. Corbels without shear reinforcement failed suddenly and catastrophically shortly after reaching their maximum loads. When stirrups were used as shear reinforcement, in corbels A2, A3, B2, and B3, failure was less catastrophic. Increasing the number of stirrups from one to two did not appear to show improvement in the ductility of the corbels, but strength of Corbels A3 and B3 increased. Corbels A4 and B4 were reinforced with 0.2% volume fraction of carbon fibers. It can be seen that both ductility and strength were improved by addition of carbon fibers. When fiber volume increased to 0.4%, both ductility and strength were improved. It was necessary to increase the volume of carbon fibers to achieve considerable improvement in both ductility and strength. It was noticed through the tests that adequate warning signs can be observed in fibrous concrete corbels, and this is a safety aspect of considerable importance.
3.4. Steel Strains

The strain in a typical main steel bar and stirrup for the corbels of group A are shown in Figure 8. As shown in the figure the behavior of all the specimens was similar up to the crack stage. The curves were steepest and terminated at the occurrence of the first crack. After the formation of inclined shear cracks, an abrupt change in the steel strain was recorded. It can be clearly seen from strain curves of Corbel A2 that for the same load level the recorded tensile strain in the main bar is greater than that...
recorded in the secondary horizontal stirrup. The main steel bar strain measurements for all corbels at the same applied load level decreased with the increase in number of stirrups and volume fraction of fibers. It can be indicated that main steel bars yielded near the maximum applied loads. However, it is also clear from Figure that the stirrups in Corbel A2 did not yield.

4. Statistical analysis

To validate the experimental work a theoretical analysis were carried out using nonlinear regression analysis. The results of corbels tested in this study and previous research work (Kriz and Raths 1965; Mattock et al. 1976; Young et al. 1985; Fattuhi 1986; Fattuhi, and Hughes 1989; Chakrabarti et al. 1989; Zeller 1991; Young and Balguru 1994; Muhammad 1998; Yousif et al. 2004; Aziz and Othman 2010; Zahawi 2011) are included in the analysis. The literature showed that the shear strength of corbels depended on many parameters that included their width \((b)\) and depth \((h)\), strengths of concrete \((f'_c)\) and steel yield strength \((f_y)\), shear span-to-depth \((a/d)\) ratio, volumes of main and secondary bars \((\rho_w \text{ and } \rho_h)\), and volume of fibers. Since the volume and type of fiber mainly affect the tensile strength \((f_{ct})\) of concrete, the latter parameter was taken as the principal criterion of performance. Nonlinear regression analysis was adopted to relate the shear strength in term of the effecting parameters. During this process, different computer computations were used to arrive at a suitable strength equation. Hence, the following equation was selected:

\[
V_n = \kappa_1 \left( f_{ct} b d \right) \left( \rho_w f_{yw} d f'_c \right) + \kappa_2 \rho_h f_{yh} \left( \frac{d}{a} \right)^{k_3}
\]

Where \(V_n\) is the nominal shear strength of a corbel; \(k_1, k_2\) and \(k_3\) = constants. Their values \((k_1 = 0.0067, k_2 = 26913, k_3 = 0.4556)\) were obtained from regression analysis.

The ratio of the experimental load-carrying capacities of all corbels tested and the results calculated by the proposed equation \((V_{exp.}/V_{pred.})\) shows that the two sets of values are in satisfactory agreement as shown in Figure 9. The maximum variation between the experimental and calculated shear capacities was about 21.6% for all specimens. The proposed equation compared with ACI 318-14 and the comparison shows that ACI equations have the higher COV of 36% for all 239 concrete corbels which included in this analysis.
5. CONCLUSION

Based on the experimental results of this investigation the following conclusions can be drawn:

1. Increasing in concrete compressive strength from 37.1 MPa to 52 MPa and shear reinforcement index from zero to 2.141 leads to increase in corbel shear strength to about 30% and 16% respectively.

2. An enhancement can be seen in the performance of the corbels with fibrous concrete in term of strength and ductility. The ultimate strength associated with 0.4% carbon fibers causes an increase about 6.6% and 9.3% for concrete compressive strength of 37.1 MPa and 52.0 MPa respectively.

3. It was found that the addition of carbon fiber delays the formation of the inclined shear cracks of fibrous corbels relative to non-fibrous corbels to about 69 % for 0.4% volume fraction.

4. The recorded tensile strain in the main bars is greater than that recorded in the secondary stirrups.

5. An equation was proposed for predicting the ultimate shear strength of the reinforced concrete corbels subjected to vertical load. The equation was compared with equations given by ACI 318-14. The proposed equation has lower COV of about 21.6%.

REFERENCES

ACI (2014): ACI Committee 318. Building Code Requirements for Structural Concrete. American Concrete Institute. Farmington Hills, Mich., 193.

ACI (2002): ACI 544.1R-96 State-of-the-Art Report on Fiber Reinforced Concrete.

Al-Zahawi S.K. (2011). Shear Strength and Behavior of Reinforced Concrete Corbels with and without Carbon Fibers. PhD Thesis, University of Sulaimani, Kurdistan-Iraq.

Aziz, O. Q. and Othman, Z. S. (2010). Ultimate Shear Strength of Reinforced High Strength Concrete Corbels Subjected to Vertical Load. Al-Rafidain Eng. J., 18 (1), 1-12.

Campione, G., La Mendola, L., and Papia, M. (2005). Flexural Behaviour of Concrete Corbels Containing Steel Fibers or Wrapped with FRP Sheets. J. Mater. and Struct., 38(280), 617-625.
Campione, G., Mendola, L., and Mangiavillano, M. (2007). Steel Fiber-Reinforced Concrete Corbels: Experimental Behavior and Shear Strength Prediction. J. ACI Struct., 104 (5), 570-579.

Campione, G. (2009). Performance of Steel Fibrous Reinforced Concrete Corbels Subjected to Vertical and Horizontal Loads. J. Struct. Eng., 135(5), 519-529.

Chakrabarti, P. R., Farahani, D. J., and Kashou, S. I., (1989). Reinforced and Precompressed Concrete Corbels- an Experimental Study. ACI Stru.J., 86(4), 405-412.

Fattuhi, N. I. (1986). Corbels with Shear Reinforcement in the form of Stirrups or Fibers, Third International Symposium on Developments in Fiber Reinforced Cement and Concrete, Sheffield, 13-17 July, V. 2, Paper 8.8.

Fattuhi, N. I. and Hughes, B. P. (1989). Ductility of Reinforced Concrete Corbels Containing Either Steel Fibers or Stirrups. J. ACI Struct., 86(6), 644-651.

Fattuhi, N. I. (1990a). Column Load Effect on Reinforced Concrete Corbels. J. Struct. Eng., 116(1), 188-197.

Fattuhi, N. I. (1990b). Strength of SFRC Corbels Subjected to Vertical Load. J. Struct. Eng., 116(3), 701-718.

Fattuhi, N. I. (1994). Reinforced Corbels Made with Plain and Fibrous Concretes. J. ACI Struct., 91(5), 530-536.

Kriz, L. B. and Raths, C. H. (1965). Connections in Precast Concrete Structure-Strength of Corbels. PCI J., 10 (1), 16-61.

Kumar, S. (2004). Shear strength of reinforced steel fibrous concrete corbels without shear reinforcement. Journal of the Institution of Engineers, India. Civil Engineering Division, 85(nov), 202-212.

Mattock, A.H., Chen, K.C. and Soongswang, K. (1976). The behavior of reinforced concrete corbels. PCI Journal, 21(2), 52-77.

Muhammad, A. H. (1998). Behavior and Strength of High-Strength Fiber Reinforced Concrete Corbels Subjected to Monotonic or Cyclic (repeated) Loading. PhD thesis presented to the University of Technology, Baghdad, Dec., 1-172.

Yang, J., Lee, J., Yoon, Y., Cook, W.; and Mitchell D. (2012). Influence of Steel Fibers and Headed Bars on the Serviceability of High-Strength Concrete Corbels. J. Struct. Eng., 138(1), 123-129.

Young, Y. K. and Balaguru, P. (1994). Behavior of Reinforced High-Strength Concrete Corbels. J. Stru. Eng. ASCE, 120(4), 1182-1201.

Young, Y. K., McCloskey, D.H., and Naway, E. G. (1985). Reinforced Corbels of High-Strength Concrete. Special Publication, 87, 197-212.

Yousif, A. R., Aziz, O. Q., and Muhammad, A. H. (2004). Size Effect on Shear Failure of High-Strength Reinforced Concrete Corbels without stirrups. Zanco Journal of Pure and Applied Sciences.16(1), 5-15.

Zeller, W. (1991). Conclusions from Tests on Corbels. IABSE Colloquium, Structural Concrete, International Association for Bridge and Structural Engineering, Stuttgart, 577-582.