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Analysis, Behavior, Strengthening and repairing of Reinforced Concrete Corbels: Comprehensive Review

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ABSTRACT

In this review, an extensive survey on the theoretical models and approaches that were proposed in literature to study the behavior of RC corbels has been presented. Such approaches included the shear friction approach, strut and tie model, finite element and Neural networks. Moreover, the review has been extended to consider the studies conducted experimentally by researchers and scholars to investigate the response of the RC corbels. Furthermore, various proposals that were suggested regarding strengthening and repairing of RC corbels have been discussed. Different materials have been used to improve the performance of RC corbels, such as steel fibers, FRP composites, NSM steel bars, NSM CFRP bars and composite sections have been considered. The most important findings reported in the relevant literature have been summarized. In addition, several recommendations to extend the studies concerning the RC corbel to improve the knowledge about the behavior of this significant structural member have been presented.

1 Introduction

ACI318-19 code [1] defined Brackets and corbels as" short cantilevers that tend to act as simple trusses or deep beams, rather than beams ". Such members have small shear span-to-effective depth ratios ($a_v/d \leqslant 2.0$.). Moreover, Corbels are considered as D-regions at which there is a considerable disturbance and non-uniformity in stress counter lines occurred. These regions need to be designed to more approaches rather than Bernoulli theory. D-region category, Fig. 1, includes various structural elements such as the beam-column connections, deep beams, short columns or corbels, dapped ends, stepped beams, beams with openings, corners, shear walls, abutments, pile caps [2-5]. The most two adopted methods are shear-friction method [6] and the strut and tie models [1]. The shear friction approach is a semi-imperial method. Strut-and-tie modeling method, which evolved on truss-model approach, has generally been preferred for the design of complex reinforced concrete structures and structural elements that have critical shear behavior. Nevertheless, the designer requires

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adequate knowledge and experience to use this approach. Corbels have been used in various applications, amongst are high-rise building, precast industry, Industrial buildings, foundations and bridges. According to the provisions of ACI318- 19, it is allowed to use the shear friction approach up to a value of shear-slenderness ratio of 1.0. Beyond which, the STM model should be adopted.

Several studies [7] reported that a corbel might fail by crushing of the horizontal and diagonal concrete strut, crushing of the compression zone, and yielding of principal tensile reinforcement. Such modes of failure are listed in Table (1) with the expected causes and illustrative figure for each one.

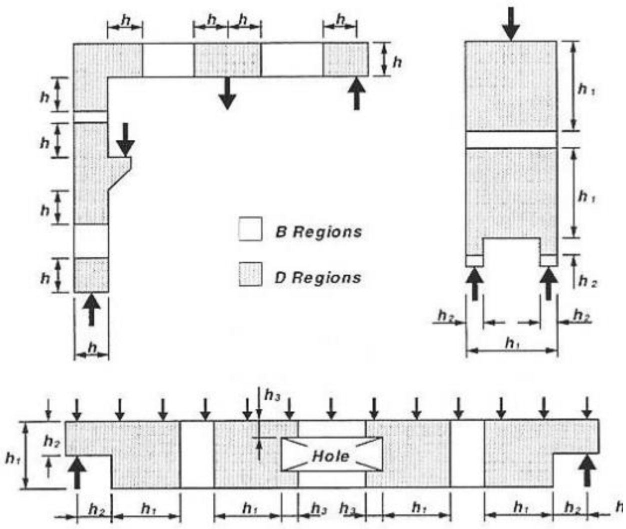
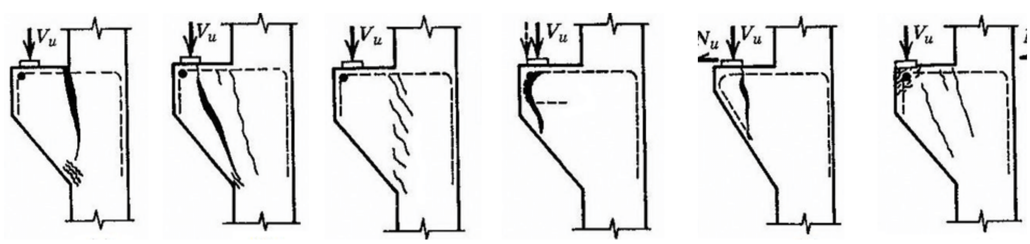


Fig. 1 – Different examples of D-regions [4]

Table 1 – Mode of failure of RC corbels (adapted from Kris [7])

Mode of failure		Causes
1-Flexture Failure		1- Small amount of main steel.
		2- a/d>1
2-Diagonal Splitting		1- Low compressive strength with high main steel.
		2- Small amount of steel crossing the strut.
3-Shear Failure		1- Small amount of stirrups.
		2- a/d<1
4-local failure	Type 1	1- Loss of anchorage.
		2- Lack in the detailing of embedded length.
	Type 2	1- Small thickness of corbel.
		2- High value of horizontal load.
	Type 3	1- Lack in the seat plate detailing.



Mode 1 Mode 2 Mode 3 Mode 4-type1 Mode 4-type2 Mode 4-type 3

2 Approaches and Methodologies on the behavior of RC corbels

2.1 Shear friction method

One of the earliest proposals to predict the behavior and design of reinforced concrete corbels was suggested in 1965 when Kriz and Raths [7], have presented the results of experimental study of 124 corbels subjected to vertical loads only and 71 corbels subjected to combined vertical and horizontal loads. Several parameters were considered including: reinforcement ratio, a/d ratio (shear span to the effective depth), stirrup reinforcement amount and distribution, corbel size and shape, and the ratio of horizontal to the vertical applied load. It was concluded that the maximum shear stress in a corbel is a function of reinforcement ratio, the (a/d), concrete grade and the ratio of (horizontal/vertical) loads and can be expressed as

$$V_u = \emptyset\left[6.5bd\sqrt{f_c'}\left(1 - 0.5^{d/a}\right)\frac{(1000\rho)^{1/3+0.4H/V}}{10^{0.8H/V}}\right] \tag{1}$$

Moreover, the existence of any horizontal tensile force in combination with the vertical reaction may affect significantly the corbel strength. Thus, it should be considered when designing a corbel. Fig. (2) shows the proposed SF model.

In 1976, Mattock [8] has suggested the first version, Fig. (3), of what was called later as " shear friction" design procedure of RC corbels. Such proposal was based on results of the experimental study achieved by Mattock et. al. [9] and on shear transfer across a plane which is subjected to moment and direct tension. This method is still used up to this date and was recommended in the successive versions of ACI 318 code to be valid when a/d <1.0.

This procedure can be summarized by the following steps:

1. The ultimate shear stress in interface plane due to factored load (v_u) is calculated as

$$v_u = Min(\frac{V_u}{\emptyset bd}; 0.2 * fc)\ ; \emptyset = 0.75 \tag{2}$$

2. The area of main steel, *As*, is expressed as:

$$A_s = Max\left(Av_f + A_n; \frac{2}{3}A_{vh} + A_n; 0.04\frac{f_c'}{f_y}\ bd\right) \tag{3}$$

$$A_{vh} = V_u/\Phi f_y \tag{3a}$$

$$A_n = N_u/\Phi f_y \tag{3b}$$

$$A_{vf} = Max(\{Vn/(\Phi*0.8) - K\ b\ d\}/fy; 0.2\ bd\ /fy) \tag{3c}$$

K= 0.5, 0.25 and 0.31 for normal weight; all-lightweight and sand lightweight concrete respectively.

3. The horizontal stirrups in the lower two-thirds of the depth of the corbel, having area:

$$Ah = 0.5(As - An) \tag{4}$$

This reinforcement is to be uniformly distributed within the two-thirds of the effective depth of the interface adjacent to the main reinforcement.

2.2 Strut and Tie model based studies

In 1985, Yong et. al. [10] have presented a study on RC corbels with concrete grade of 41.4 N/mm2. The applicability of the ACI Code and the truss analogy theory proposed by Hagberg [11] were checked. RC corbels with grades of concrete ranged in (41.7- 82.7) N/mm2 and a/d = 0.39 were considered. Results revealed that the Provisions of ACI Code are conservative and that the truss analogy model estimated values that were less conservative than the ACI equations.

Solanki and Sabnis [12] presented a simplified truss analogy for RC corbels, Fig. (4), based on the equilibrium of forces as follows:

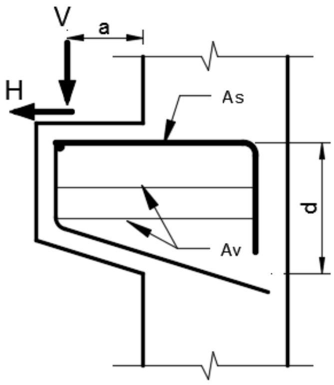


Fig. 2 – Kriz and Raths, model [7]

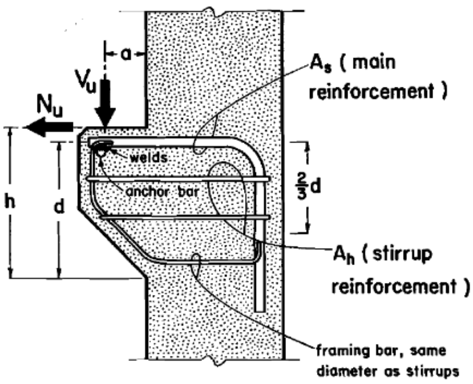


Fig. 3 – Mattock Model [8]

$$\frac{bd\,f_c'}{V_u} = \frac{4.45}{\beta_1}\left(1 + \frac{N_u}{V_u} * \frac{\Delta h}{a}\right)\sqrt{0.9^2 + (a/d)^2} \tag{5}$$

This proposal was validated for a/d < 1 .0 and, with vertical and horizontal as well as inclined loads. It was deduced that when a/d < 0.5, some horizontal hoops are needed and that the plane of principal shear stress was at I7o to the vertical.

A modified strut-and-tie simulation was proposed by Ali and White [13] to estimate the RC corbel strength. Such model considered the variable width of the compression strut. Such proposal, Fig. (5), is based on superimposing the developed strut width and its degradation in terms of tensile strains. The modified strut width was expressed as:

$$\frac{b_{st}}{b_{corr}} = \begin{cases} \frac{b_{st}}{b_{max}} + \left(\frac{\varepsilon}{\varepsilon_y}\right)^2\left(1 - \frac{b_{st}}{b_{max}}\right) & 0 \le \varepsilon \le \varepsilon_y \\ 1 & \varepsilon > \varepsilon_y \end{cases} \tag{6}$$

$$b_{st} \approx b' \sin\theta \tag{6a}$$

$$b_{max} = 0.6 * \frac{h}{2}\left[1 + \frac{0.05}{(a/h)^2}\right] \le h \tag{6b}$$

It was reported that the proposed method yielded better prediction of strength compared to the STM provisions Canadian CAN3-1994, European CEB-FIB-1990 and shear-friction model of ACI 318-1995.

In 2006, a modified model to determine the shear capacity of RC brackets or corbels has been proposed by Russo et al. [14]. This model was based on combining shear strength contribution of the strut-and-tie mechanism due to the cracked concrete and principal reinforcement, and the strength contribution due to stirrups. Fig. (6) shows the proposed STM model. Concrete contribution was expressed using limiting shear strength relations. Whereas, the contribution of the main reinforcement is obtained by applying equilibrium conditions of the STM model in the presence of the horizontal stirrups. The shear resistance was expressed as:

$$v_u = c_1\left(k\chi f'_c \cos\theta + c_2\rho_h f_{yv} \cot\theta\right) \tag{7}$$

In which:

$$k = \sqrt{\left(n\rho_f\right)^2 + 2n\rho_f} - n\rho_f \tag{7a}$$

$$\chi = \begin{cases} -\frac{0.9}{\sqrt{1+400\varepsilon_r}} & for\ f'_c < 42\ MPa \\ -\frac{5.8}{\sqrt{1+400\varepsilon_r}} & for\ f'_c \ge 42\ MPa \end{cases} \quad \delta = \sum_{i=1}^{s} e^H(\omega_t).e(\omega_t) \tag{7b}$$

It was concluded that the horizontal hoops contribution depends on the angle between the vertical direction and the concrete strut.

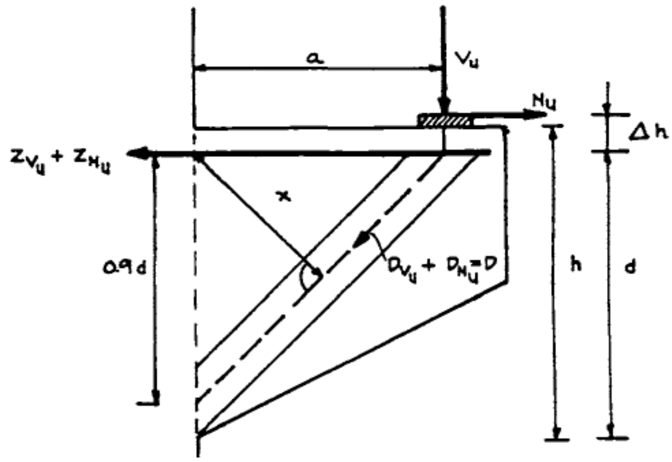


Fig. 4 – Solanki and Sabnis model [12]

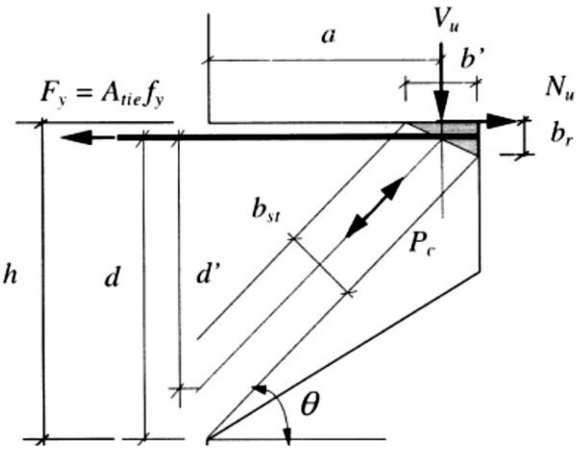


Fig. 5 – Ali and White model [13]

In 2009, a modified softened strut-and-tie model, Fig. (7), was proposed by Lu and Lin [15] to determine the shear capacity of RC corbels. The results of testing thirteen RC corbels with a shear span/depth ratio exceeding one were presented. Several variables were investigated including the grade of concrete, shear span-/depth ratio, and the effect of vertical hoops. It was reported that the shear capacity and stiffness of corbels enhanced with higher grades of concrete and more perimeter of vertical hoops and with reducing shear span/depth ratio.

In the proposed model, the relationship between vertical and horizontal shears was expressed as:

$$\frac{V_{dv}}{V_{dh}} \approx \frac{jd}{\acute{a}} \tag{8}$$

F_h, F_{yh} and A_{th} are the tension, yielding forces and the cross sec. area of the horizontal tie respectively.

According to Lin et al. 2003, strength of the "diagonal compression strut" may be predicted as follows:

$$C_d = (K_h + K_v - 1) f_c' A_{str} \tag{9}$$

The horizontal and vertical tie indices; Kh and Kv; can be expressed as:

$$\bar{F}_V \ and \ \bar{F}_h = f(\theta \ . Asv. fyv. Astr. f'c) \tag{9a}$$

θ is the angle of concrete strut is expressed in Eq. (9a);

$$\theta = \tan^{-1}\left(\frac{jd}{a}\right) \tag{9b}$$

$$A_{str} = t_s * b_s \tag{9c}$$

$$t_s = kd \tag{9d}$$

$$Vd_{v\,calc} \ = Cd \ sin \ \theta \tag{10}$$

It was reported that both the proposed model and ACI 318-08 approach could efficiently estimate the shear capacity of corbels with a/d exceeds one. Moreover, it was found that adopting a high a/d and a low ρ resulted in more ductile flexural failure, and that a diagonal compression failure may occur in a corbel when using a low a/d and a high ρ.

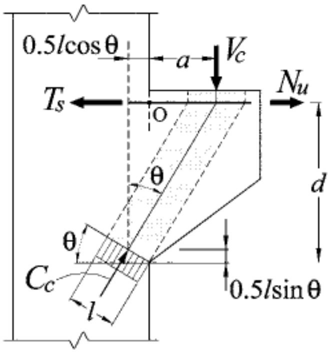


Fig. 6 – Russo et.al. STM model [14]

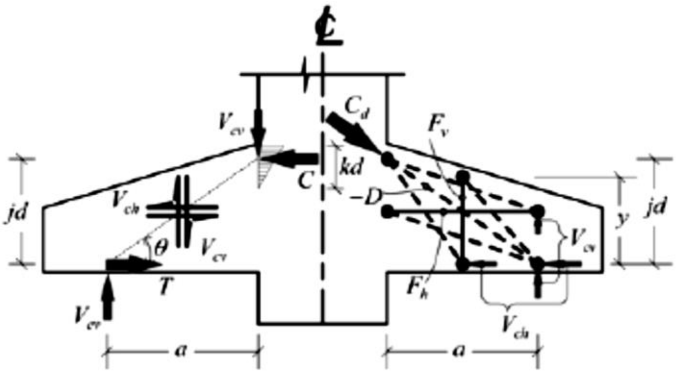


Fig. 7 – Lu and Lin model [15]

In 2012, a macro-mechanical STM technique was proposed by Khalifa [16] to analyze the fibrous HSC corbels. The fibers were used as partial replacement for the horizontal hoops. Fiber characteristics have been considered including the fiber content, length of fiber, and fiber diameter, non-uniform distribution of fibers, in addition to the shear span/depth ratio. Fig. (8) shows the main elements of the proposed model.

In this model, the force in the horizontal tie is expressed as:

$$T_h = \left[(2/3)\left(f_{cf}/\gamma_{ct}\right)b(d - a/0.8)\right]J_t;\ Jt{=}0.80 \tag{11}$$

$$Q_v = D_c \sin\theta + T_h \tan\theta \tag{12}$$

$$D_c \sin\theta / T_h \tan\theta = R_c/R_t \tag{12a}$$

$$R_c\ and\ R_t = f(\theta) \tag{12b}$$

It was reported that the enhancement in failure load was increased up to fiber content of 1.5%, and that the optimum aspect ratio of fibers was 55-60. Moreover, it was recommended to use more fiber content with higher aspect ratio rather than using concrete grade more than 50 N/mm2.

He, et. al. [17] have proposed a theoretical model that combined direct strut and truss mechanisms as shown in Fig. (9). Direct equations are presented to predict the contribution of each mechanism, based on maximizing the strength capacity of the proposed model. The ultimate shear capacity of the concrete corbel can be expressed as:

$$\frac{1}{V_u} = \frac{1}{V_1^*} + \frac{1}{V_2^*} \tag{13}$$

$$V_1^* = \frac{\tan\theta}{1-\gamma_{ht}\sin^2\theta/2}\nu f'_c bd \tag{13a}$$

$$V_2^* = \frac{2n(1-0.6\gamma_{ht})\tan\theta}{(1-\gamma_{ht}\sin^2\theta/2)^2}\frac{(\nu f'_c)^2 bd}{f_y} \tag{13b}$$

n; modular ratio; $\gamma_{ht} = f(\theta)$; ν: effectiveness factor

It was concluded that the value of a/d ratio plays a dominant role in the distribution of load between the truss and direct mechanisms.

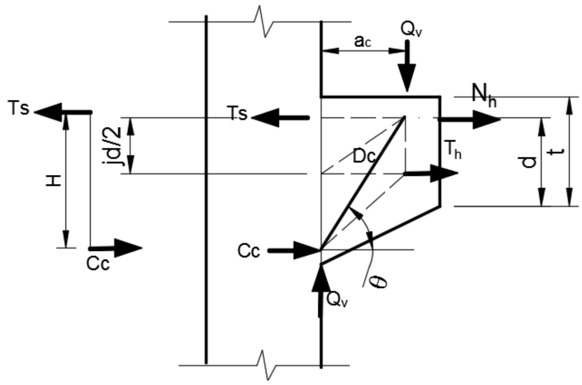
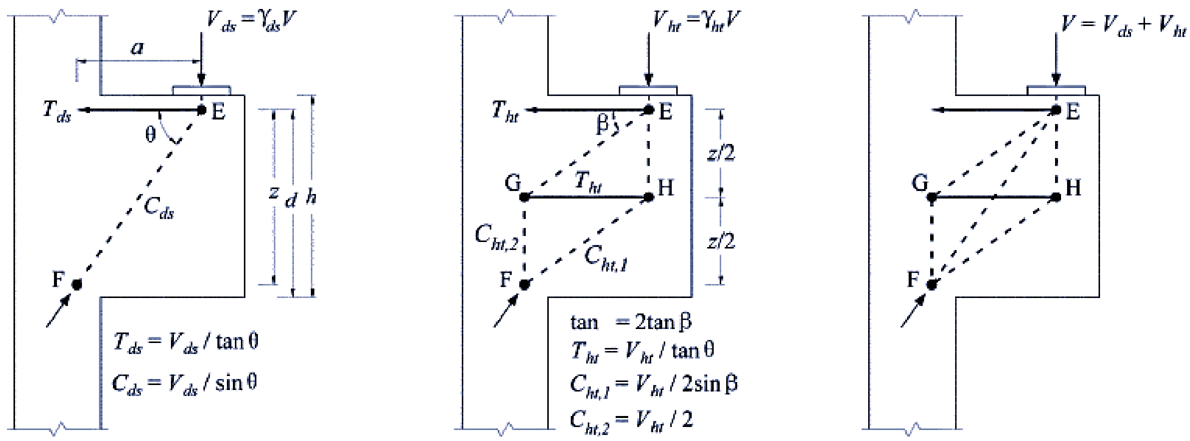


Fig. 8 – Strut and tie model of Khalifa [16]



a) Direct model ***b) Horizontal STM model*** ***c) Combined model***

Fig. 9 – Strut and tie model of He et al. [17]

Kassem [18] has proposed a model based on the strut-and-tie based method, Fig. 10, and the secant stiffness formulation that incorporated strain compatibility and constitutive laws of cracked RC. The load-carrying capacity was evaluated as limited by the failure modes associated with nodal crushing, yielding of the longitudinal principal reinforcement, as well as crushing or splitting of the diagonal strut.

In this proposal, the ascending branch of the stress strain curve of concrete is expressed as:

$$\sigma_2 = \psi f'_c \left[2\left(\frac{\varepsilon_2}{\psi\varepsilon_0}\right) - \left(\frac{\varepsilon_2}{\psi\varepsilon_0}\right)^2\right]; \frac{\varepsilon_2}{\psi\varepsilon_0} \leq 1 \quad (14)$$

$$\sigma_2 = \psi f'_c \left[1 - \left(\frac{(\varepsilon_2/\psi\varepsilon_0)-1}{\frac{4}{\psi}-1}\right)^2\right]; \frac{\varepsilon_2}{\psi}\varepsilon_0 \geq 1 \quad (15)$$

In which:

$\psi; k_c; k_f$ *and* ε_0 *are functions of* θ

It was reported that the proposed method is more efficient than the shear friction approach adopted by the ACI 318-11, and the STM requirements in various codes (Australian, American, Euro code, Canadian and New Zealand). Furthermore, the predictions by the proposed model were adequate for a/d < ratios up to 2.

In 2017, Mehmet [19] has proposed an integrated approach that comprised the topology optimization and STM methods to determine the reinforcement layout of a corbel model. It was observed that the proposed method presented more adequate results than the conventional approach.

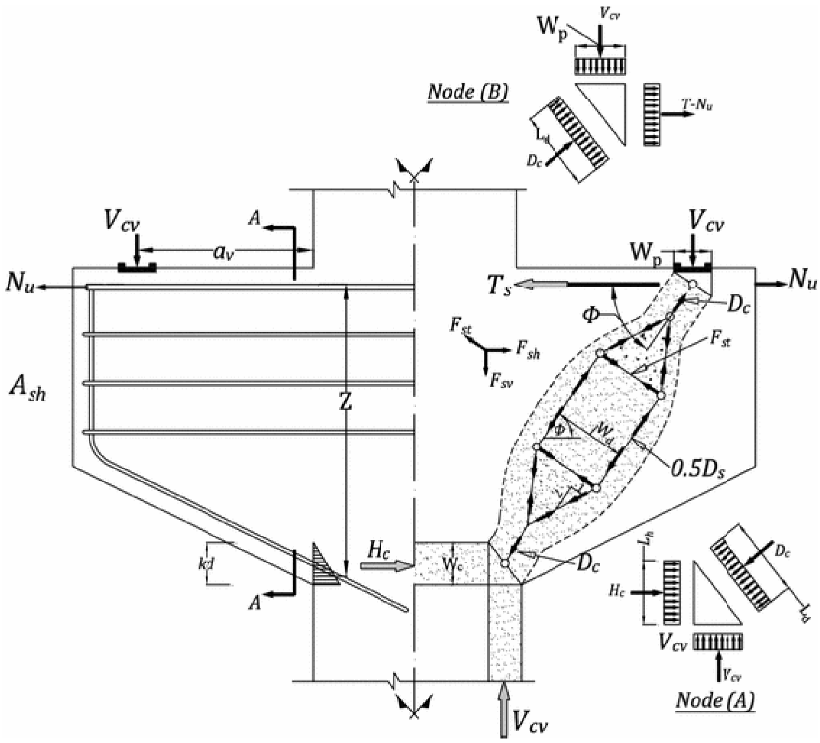


Fig. 10 – Strut and tie model of Kassem [18]

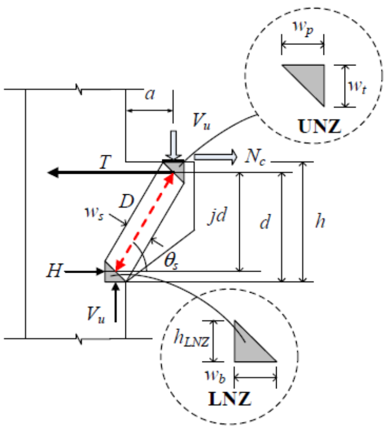


Fig. 11 – STM model of Chetchotisak. et al. [20]

Wilson et al. [21] have conducted an experimental study to evaluate the STM approach for RC corbels compared to the shear friction ACI 318-14 design method. It was concluded that corbels designed according to STM, yielded good agreement comparing to those, which were designed adopting the shear-friction approach. Furthermore, it was observed that the tension and shear reinforcing steel bars determined by STM approach of ACI 318-14 was found to be adequate to avoid premature and brittle failure of corbels.

Chetchotisak. et al. [20] have proposed a modified STM model, Fig. (11), for predicting the maximum shear capacity of RC corbels based on the interaction between the load capacity of the strut that represented compression force of concrete, the tension tie of the main steel reinforcement and the effects of the horizontal force. Also, the quantity of the shear reinforcement in terms the horizontal and vertical closed links has been considered. The predictions obtained for 302 corbels considered from literature with the ACI 318 code. It was concluded that shear strength of RC corbels was greater in precision and better in uniformity than the STM computed from ACI 318-14.

2.3 Finite Element Method based studies

Prasad et al. [22] have used a nonlinear FE approach with constitutive formulation based on an elastic-plastic-cracking model. Cracking has been simulated by smeared model and that the total strains in concrete were expressed in terms of elastic strains, crack strains and plastic strains as in equation (16a). Specimens with (a/d) value ranged in (0.366-0.79) have been tested. The horizontal, diagonal and vertical stirrups were considered in the study.

$$\Delta\epsilon = \{\Delta\epsilon^{e}\} + \{\Delta\epsilon^{cr}\} + \{\Delta\epsilon^{p}\} \tag{16}$$

The stress increment can be calculated as:

$$\Delta\sigma = [D^{ecr}]\left[[I] - \frac{\left\{\frac{\partial g}{\partial\sigma}\right\}\left\{\frac{\partial f}{\partial\sigma}\right\}^{T}[D^{ecr}]}{A+\left\{\frac{\partial f}{\partial\sigma}\right\}^{T}[D^{ecr}]\left\{\frac{\partial f}{\partial\sigma}\right\}}\right]\Delta\epsilon \tag{16a}$$

Syroka et.al. [23] have presented quasi-static FE-formulations to investigate the behavior of short RC corbels with or without shear reinforcement. Concrete has been simulated using three constitutive models which are: an isotropic elasto-plastic, an isotropic damage and an anisotropic smeared crack model. The effects of the characteristic length, bond between concrete and steel, fracture energy and shear reinforcement were considered. Moreover, the slip has been considered and it was represented using path described in Fig. (12). It was concluded that the elasto - plastic model yielded good agreement with experimental results. An increase of a characteristic length slightly increased the ultimate vertical force and significantly width of localized zones. The presence of horizontal stirrups increased the vertical failure force by 50% and ductility of reinforced concrete corbels.

$$\tau(s) = \tau_{max}\,({}^{s}/_{s_1})^{\alpha} \;\; for\; 0 \leq s \leq s_1 \tag{17}$$

s_1=0.6 mm, s_2=0.8 mm, s_3=1 mm,α=0.4,

$\tau_{max} = 2\sqrt{f_{cu}}\;\; ; \tau_{f} = 2.09\; MPa$

Canha et. al. [24] have investigated the response of HSC corbels using the FE software ATENA. A comparison study was made with the experimental results of one hundred corbels available in literature. Several parameters have been discussed including the shear span-/effective depth ratio, the ratio of main reinforcement, the grade of concrete and the contribution of horizontal hoop reinforcements. It was concluded that the main reinforcing steel and the grade of concrete; the horizontal hoop reinforcement both present a positive effect on the strength of corbels. Also, It was observed that larger a/d ratio adversely affected the failure load. Moreover, it was reported that the vertical hoop reinforcement has a considerable effect only on the cracking propagation and ductility of the corbels.

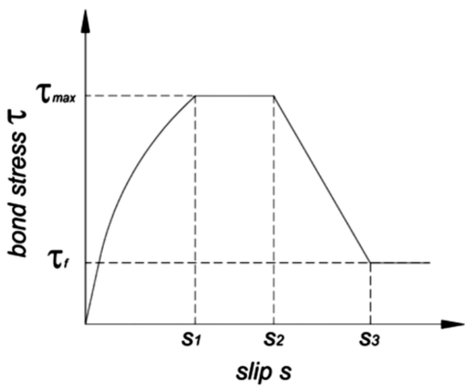


Fig. 12 – Syroka et al. slip model [22]

In 2020, a nonlinear constitutive models was proposed by Beshara et. al. [25] to consider the steel fiber reinforced concrete (SFRC) in compression and tension. The models were implemented using ANSYS to study the behavior of SFRC corbels under monotonic static loading. Several conclusions were reported, amongst were: increasing concrete compressive strength from 30 N/mm2 to 40 N/mm2 and 52.9 N/mm2 improved shear capacity by 27% and 45% respectively and the toughness by 54% and 107% respectively. Moreover, it was reported that using concrete with fiber of volume (Vf) 0.5% and 1% improved the shear capacity by 15% and 31% respectively compared to corbel without fibers. In addition, a significant enhancement in toughness was obtained by 194% and 512% for corbels with horizontal hoops (ρh) = 1.7% and 4.9% respectively. In addition, the corbel ultimate shear strength was improved by 20% and 32.5% compared to corbel without hoops. Regarding effect of (a/d) ratio, it was found out that using corbels with (a/d) = 0.7 and 0.928 decreased the shear capacity by 16% and 36% respectively, and reduced the toughness by 4% and 22% respectively, when compared to corbels with (a/d) = 0.5.

2.4 Studies based on Regression Analysis and Neural network

In 2010, Kumar and Barai [26] have developed an artificial neural network (ANN) model to predict the ultimate shear capacity of steel fiber RC corbels without shear reinforcing steel and subjected to vertical loads. The programming software MATLAB was used to achieve the nonlinear analysis. The non-dimensional shear strength in functional form can be expressed as:

$$F(\alpha) = \frac{V_u a}{kbd^2 f'_c \cos\theta} = 0.4360\alpha^{0.6963} \quad when\ \alpha \le 1.36 \tag{18a}$$

$$F(\alpha) = \frac{V_u a}{kbd^2 f'_c \cos\theta} = 0.5092\alpha^{0.1913} \quad when\ \alpha > 1.36 \tag{18b}$$

$$j = \frac{0.4360\alpha^{0.6963}}{k_1} \quad when\ \alpha \le 1.36 \tag{19a}$$

$$j = \frac{0.5092\alpha^{0.1913}}{k_1} \quad when\ \alpha > 1.36 \tag{19b}$$

α: Plasticity coefficient = $\varepsilon_{cc}/\varepsilon_{ce}$

It was concluded that the suggested model estimated the response with accuracy (-20% to +10%). In addition, a higher shear capacity was obtained when using high grades of concrete, higher ratios of main steel and higher content of steel fiber and smaller values of shear span /effective depth ratio. Furthermore, the effect of the main steel on the SFRC corbels was most influential when it was increased to 1.3%. Beyond this value, the shear capacity was still constant. Moreover, the improvement shear capacity was more pronounced when adopting small values of grades of concrete.

Aliewi in 2014 [27] has carried out experimental and theoretical investigations to study the behavior and load carrying capacity of fibrous and non-fibrous self-compacting reinforced concrete corbels subjected to vertical loading. An equation was proposed to predict the nominal shear strength of fibrous and non-fibrous self-compacting reinforced concrete corbels based on the experimental data as follows:

$$V_n = \frac{1}{30}(b_w d)^{0.45} f_{ct}^{\ 0.75}\left[\left(\frac{\rho_w f_{y\,d}}{90} + 1000\,\rho_h\, f_{yh}\right)\frac{d}{a}\right]^{\frac{1}{3}} \tag{20}$$

Aliewi [28] has proposed a modified formula to estimate the ultimate capacity of RC corbels with the aid of nonlinear regression analysis (NRE) of 245 previously published experimental test results. Several parameters have been considered including most of those that may affect the ultimate shear strength as follows:

$$V_n = (\frac{27}{800}\left(f'_c{}^{1.31} + 24\rho_w f_y + \rho h\, f_y\, h\right)(2.8)^{-a/d}\left(\frac{k}{h}\right)^{0.015} * (1 + 0.4F)bd \tag{21}$$

It was reported that the proposed formula was more adequate, safe and economic than the ACI 318 usual equations. In addition, the suggested equation yielded better agreement with experimental test results.

3 Experimental Studies Concerned the Behavior of RC Corbels.

Many researchers studied the performance and response of reinforced concrete corbel. Such studies discussed the effect of the most influencing parameters on the shear behavior of corbel including shear span to effective depth ratio (a/d), main and shear reinforcement ratio, compressive strength of concrete, type of loading.

Mattock, et al. [9] have considered the influence of both horizontal and vertical loading on the response RC corbels. Twenty-eight corbel specimens were examined, of which 26 included the horizontal closed links as shear reinforcement. Variables inspected were the aggregate type, the amount of main tensile, quantity of the stirrup reinforcements, the shear span to depth ratio, and the ratio of the vertical load to the horizontal load. Based on the findings of the study, a limited value of horizontal stirrups was suggested to avoid brittle failure. Stirrups need to be distributed uniformly within (2/3) of the effective depth of the corbel section, nearest to the main steel reinforcement.

Clottey [29] has studied the performance of lightweight concrete corbels subjected to static and repeated loads. A total of 36 sandy light –weight corbels were tested with a/d values ranged in (0.31-0.75) and compressive strength of 48 N/mm2 of concrete weight of 1920 kg/m3. It was concluded that the strength and behavior of reinforced sand-lightweight concrete corbels are affected by both the (a/d) ratio and the reinforcement ratio as well as the presence of compression reinforcement. Thus, at low shear span-to-effective depth ratios the presence of compression reinforcement in a lightweight concrete corbel appears to be beneficial to its behavior and its load-carrying capacity. The results showed that there is an exponential relationship between the shear strength of the corbel and the a/d ratio; at lower a/d ratios, the shear capacity of a corbel is rapidly increased. Therefore, it is advantageous to use low a/d ratios. It was also observed that in corbels with high reinforcement ratio, the yield strength approached the ultimate strength resulting in a more brittle behavior and a more abrupt failure.

Fattuhi and Hughes [30] have presented the results of RC corbels under vertical loading tests for fourteen corbel specimens. Twelve were normally reinforced with main bars and ten of which contained either steel fibers or stirrups as secondary (shear) reinforcement. The volume fractions of both main and secondary reinforcement were varied. The test results indicated that the addition of fibers or stirrups improved both flexural and shear strengths and ductility of the corbels. Moreover, it was reported the corbels included steel fibers failed, mostly, following a gradual and ductile manner, and the failure mode changed from being diagonal splitting to flexural when fibers were used as a secondary reinforcement. An almost elastic-plastic behavior was obtained for corbels reinforced with a relatively large volume of steel fibers (nearly twice the volume of main bars).

Zeller [31] has tested two- sided corbels having (a/d) ratios of 0.5 and 1.0, respectively, up to failure. The main tensile steel included horizontal loops, with the same area for both specimens. Horizontal stirrups having amounts of 1/3, 1/2, and 1/3 of the main reinforcement were used for three corbels (each one is represented by one side). Vertical stirrups had been used in the fourth corbel to resist the transverse tensile stresses. The study concluded horizontal closed links which represent the shear reinforcement may be enough for corbels with strut making angle (from horizontal) more than 45o as for corbels with small shear slenderness ratio that having (a/d) ratios less in the range (0.7-0.9). Furthermore, the vertical stirrup would be more efficient when the angle of the compression strut is less than 45o from the horizontal. Also, the bearing capacity of corbels has been influenced largely by the arrangement of tension reinforcement, and that the simple "strut-and-tie" model (STM) was not able to consider the real stresses in the compression zone after diagonal splitting occurred.

In 1991, sixty full-scale corbels with steel fibers were tested by Halabi [32]. The shear span/effective depth (a/d) ranged in (0.1-1.0) and concrete strength ranged in (50 - l00) N/mm2. It was reported that all of the tested corbels failed through diagonal splitting, and that the main reinforcement and stirrups have significant effect on the strength and ductility of corbels. In some corbels, behavior has been characterized as "over-reinforced" due to small ultimate strains and lower failure load than corbels that had their steel yielded. Moreover, the addition of 1.2% or more steel fibers to high strength concrete corbels converts the mode of failure from a sudden, brittle type to a ductile mode. It also led to increments in strength by (20%-35%) and shear strength by up to 50%.

In 2000, a softened STM model was proposed by Hwang et al. [33] to study the shear strength of RC corbels. The validity of the proposed model was checked by comparisons with the results of 178 corbels that were published in literature. The variables studied included the "a/d" ratio, the concrete strength, and the amount of horizontal reinforcement. The splitting and crushing failures of the diagonal struts were discovered to be identical. Also, the ACI empirical formulae' predictions were conservative for some test data, with more obvious conservatism for corbels with a low shear span-depth ratio or those made of high-strength concrete. While, the STM model was better than the "ACI -318" approach for all the variables under comparison.

The flexural response of fibrous and non-fibrous concrete corbels has been investigated experimentally by Campione et.al. [34]. Type of concrete (NSC or HSC), steel fiber ratio and configuration and ratio of the main reinforcement have been considered as the controlling parameters. It has been observed that using steel fibers in addition to horizontal stirrups resulted in good improvement in strength and deformation capacity in RC corbels. Moreover, an analytical proposal was suggested to predict the shear capacity of FRC corbels. The proposed formulation was validated against experimental results of previously published studies.

Rezaei, et. al. [35], have conducted a study on the impact of primary and secondary reinforcements under a combination of horizontal and vertical loads. Eleven RC corbels with compressive strength of concrete 30 N/mm2 were tested. Strut and tie (STM) and the shear friction (SF) method [3] have been considered for comparison. Amongst conclusions were

1. Shear friction approach is more conservative than the STM models.
2. Based on the STM method, the required amount of the secondary reinforcement should be increased when the horizontal load is increased.
3. Shear friction approach is suitable when the horizontal force is not more than 20% of the vertical load.
4. The ultimate capacity dropped severely with the presence of high value of the horizontal load.

Salman, et al. [36], have investigated the behavior of self-compacting RC normal strength corbels without and with steel fibers by testing ten corbel specimens. Parameters considered were the steel fiber content, compressive strength of concrete, and the (a/d) ratio. It was found out that the steel fibers delayed the appearance of the cracking of corbels and increase the ultimate and the cracking loads for corbels by about 32% and 25% respectively, when the content of steel fibers increased from 0% to 0.4%. Moreover, it was reported that increasing the steel fibers content from 0% - 0.8% led to improving the cracking load and ultimate capacity by 41% and 29 % respectively. However, the corresponding enhancements were 7 % and 3 % respectively, when the volume of steel fibers increased from 0.4% - 0.8%.

In 2014, design charts for RC corbels have been developed by Fragomeni and Staden [37], based on Strut and Tie (STM) models of AS3600-2009. Concrete strengths ranging from (20- 100) N/mm2 were considered. Design limitations of AS3600-2001, and ACI318-11 design codes were also considered. Predictions of the chart with results of several previous published studies have been discussed.

The response of RC corbels subjected to repeated loadings has been studied experimentally by Al-Shaarbaf et al. [38]. Twenty-four specimens have been tested under vertical loading. Some with normal strength concrete (NSC) and high strength concrete (HSC) with vibrated or self-compacted concrete (SCC). Half of the specimens were tested under monotonic loading. The rest were tested under repeated loading under various levels (60%, 80% and 90%). Several variables were considered including shear span / effective depth(a/d) ratio, ratio of the stirrup reinforcement, grade of concrete and class of concrete (vibrated and SCC). It was concluded that horizontal hoops are necessary to prevent brittle failure of the corbels after reaching their failure loads. Moreover, for the vibrated concrete corbels, reducing the shear span /effective depth ratio (a/d) from 0.7 to 0.3, the enhancements in the cracking load were 104.7% and 154.9% for the NSC and HSC corbels respectively. While, the failure load enhanced by 65.7% and 115.7% respectively.

Abd Ghani [39] has evaluated the behavior of non-seismic precast buildings under the effect of long-distant earthquakes from Sumatera and nearfield earthquakes. Three sub-assemblages of the specimens consisting of comer, interior and exterior of precast beam-column joints, were tested under reversible in-plane lateral cyclic loading.

Direct Displacement-Based Design (DDBD) approach was utilized in developing load versus displacement curve (hysteresis loops). Subsequently, the exterior beam-column joint was retrofitted using Carbon Fiber Reinforced Polymer (CFRP) wrapping and steel plate bonding. It was concluded that the precast beam-column joints would not survive when subjected to earthquake excitation with surface-wave magnitude, more than 5.5 Scale Richter (Type 1 of spectra) which means that the beam-column joint which is designed by using BS8110 would severely damage when subjected to strong earthquake excitation.

An experimental investigation has been conducted by Lachowicz, and Godycka [40] to study the behavior of double-sided post-tensioned RC corbels. Six symmetrical specimens were tested and several variable were considered including shear span / depth (a/d) and location of prestressing steel. The test results were calibrated against the cracking and failure loads of corbels reinforced with mild steel only. It was found that the first crack initiated within (0.5–0.6) Fu for the prestressed corbels regardless of shear span / depth ratio. Whereas in corbels with mild steel cracking initialed within (0.2–0.3) Fu. Furthermore, it was reported that decreasing a/d ratio from 1.0 to 0.3, the failure load of the corbel was enhanced two times.

The shear capacity of twelve RC corbels with glass fiber reinforced polymer (GFRP) bars has been considered in 2016 by Abu Obaida [41]. Several parameters were considered including the shear span/effective depth ratio (a/d) (1 and 1.5), GFRP bar content (3 ρb , 4 ρb and 6 ρb), and grade of concrete (20 and 40) N/mm2. The study also included an analytical work to estimate the capacity of the corbels using the STM approach adopted by CSA-S806-12 code. It was concluded that:

1. An arch mechanism is developed by the formation of the main parallel diagonal shear cracks. Substantial reserve capacity was available after the formation of the main diagonal cracks indicating internal redistribution of the forces.

2. Most of the tested RC corbel specimens showed brittle failure due to concrete crushing in the diagonal compression strut.

3. Increasing the grade of concrete resulted in improvement in the shear capacity

4. Increasing the GFRP reinforcement from 3 ρb to 6 ρb, for a/d =1.0 enhanced the shear capacity by (8- 94.3) %, respectively. Whereas, for a/d=1.5, these enhancements were obtained to be ranged in (29.8- 43) %, respectively. However, for high concrete strength, with a/ d =1.0, the enhancements were obtained to be 44.4% and 21.2% when the GFRP bars content was increased from 3 ρb to 4 ρb and from 3 ρb to 6 ρb, respectively.

5. It was recommended to use web horizontal steel stirrups to control the cracks of the corbels.

In 2017, the behavior of RC corbels made of ultra-high performance steel fibers concrete (UHPSFC) with grade of 150 N/mm2 has been studied by Ridha, et al. [42]. Eleven specimens were cast and tested and the amounts of the tension reinforcement, shear reinforcement (closed stirrups), and shear slenderness ratio (a/d) were the key variables. It was found that:

The first cracking was of the flexural type that formed at or near the junction of the corbel-column, and the first cracking load may be improved with increasing the ratio of the main tension reinforcement or reducing the shear slenderness ratio.

Width of crack was reduced, stiffness of the corbel was improved, and ductility was marginally increased by adding secondary reinforcement.

Araújo et. al., [43] have presented analytical and computational modeling of five models of concrete corbels, one monolithic and four models with corbels casted separately from of the column parts. It was observed that the concrete corbels with bent tie reinforcement presented the largest gap opening in interface and that the computational model represented the monolithic concrete corbel resistance better than normative models. Moreover, it was concluded that corbels cast in a different stage from the column show greater joint gap opening than monolithic corbels, even if it does not necessarily involve a reduction in the failure load of the corbel. Design code models were conservative in terms of their evaluation of yielding strength of the main reinforcements for the models of monolithic corbels and with corbels cast in a different stage from the column when sleeves and threads spliced the main reinforcement. All design code models overestimated the strength of the strut in corbels without horizontal force.

Ali and Mahdi, [44] have discussed the shear and bending behavior of corbel's hybrid reinforced concrete system. Fourteen specimens had been tested under un-symmetrical loading. The tested specimens were grouped into two categories: Hybrid and Non-hybrid. Several variables were considered including type of concrete, type of the hybrid concrete, area hybridization in the corbel – column system and (a/d) ratio. Result proved that the shear capacity of the corbel enhanced by (10 to 41) % for samples that were hybrid with HSC, while they were increased by a range (19 to 44) % for hybrid samples homogeneous with SFRC comparison with NSC homogeneous specimens having same ratio (a/d).

Putri, [45] presented a comparison between test results of two groups of one-sided corbels (each of 2 specimens) that have been designed using conventional (SF) method and Strut and Tie Model with (a/d) ratio from (0.15 -1.5) respectively. The column load was kept constant (50 kN) and corbels was tested under monotonic loads gradually increased up to failure. The results showed that the shear capacity for specimens using the conventional method were (13.40%) greater than using the STM model and the shear capacity of both the SF and the STM methods were 1.92 and 1.66 greater than the specified load.

Dawood, [46] have studied the behavior of the RC corbel designed using the shear friction approach and Strut-and-Tie models. The main variables of the study were, compressive strength of concrete (f'c), width of corbel (b), ratio of the horizontal to vertical load (H/V), (a/d) ratio, and yield strength of the reinforcement (fy). The results showed that:

Shear friction is more conservative than STM models. Moreover, the ultimate shear capacity of corbel increased by about (59.43%) STM and (58.54%) for SF when the a/d ratio decreased from 1.9 to 0.1.

The increase of corbel width by about (100-300) % leads to improvement in shear capacity by about 54 % and 33% for STM and SF respectively.

The increase of concrete compressive strength of corbels by about (15-35) % led to enhancement in load capacity by about 50% and 26 % for STM and SF respectively.

Because corbels may fail due to tension stress on the strut or primary reinforcement tension, the response of high and normal strength concrete corbels was the same.

The load capacity of corbel increased by about 30% and 31% for STM and SF when the yield strength of the main reinforcement increased by about (400-600%).

The presence of horizontal force in corbels led to a decrease in vertical load capacity.

Lacerda et al., [47] have investigated experimentally the effect of using grout filling within the vertical interface between the corbel and the beam of the interior beam-to-column joints on the response of such semi-rigid joints when it is subjected to hogging bending moment. Four specimens were tested: two with grout filling and other two specimens without filling. Results revealed that there is a good enhancement in flexural capacity of the joints, which yielded ultimate capacity more than the predicted by usual design procedure of RC sections. It was observed that the using the grout filling had a good contribution in improvement the rotational stiffness and flexural capacity of the joints, with 5 times and 1.4 times, respectively, relative to the non-grouted connections. Moreover, the cost/benefit ratio as a function stiffness and strength reached when grouting vertical interfaces between a corbel and a beam is relatively high.

An experimental investigation has been conducted by Chagas, et al. [48] on the behavior of the segmented short precast concrete corbels. The corbels and column have been casted individually and then connected to it using unbonded post-tensioning rods as shown in Figure (13). Three specimens had been tested with compressive strength of 36 N/mm2 and a/d= 0.7. Results indicated that the suggested arrangement of corbel yielded failure lower than the control monolithic corbel by 5%. Furthermore, the proposed arrangement produced strength considerably greater than that obtained for corbel cast in two steps without prestressing.

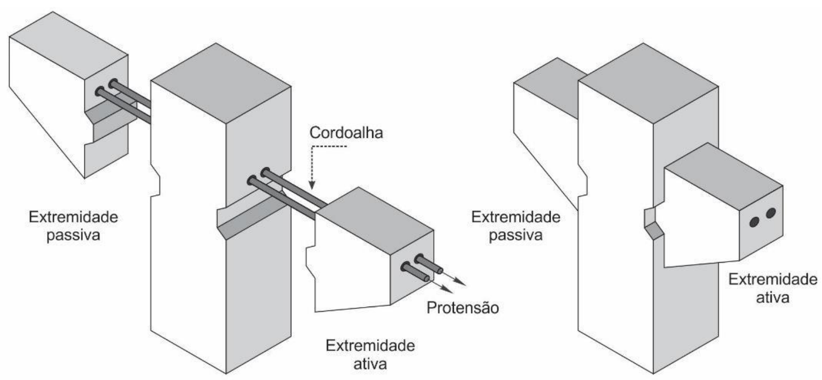


Fig. 13 – Segmental Post-tensioned corbel model [48]

The study of Abdul-Razzaq and Dawood [49] included the findings of experimental tests on three reinforced concrete corbels with variable values of (a/d) ratios (0.5 &1,1.5). The results were evaluated utilizing both shear friction (SF) and Strut-and Tie modeling (STM). According to the findings;

1. STM results showed good agreement with the experimental results compared to SF. Because it defines the mode of failure more adequately and it considers wider range of parameters affecting the performance of RC corbels a/d <2. While SF is valid for a/d<1.

2. For corbel with a/d=1, shear controlled the behavior, then a brittle failure occurred. The corbel's ductility and flexural capacity were significantly affected by a/d ratio. The behavior and failure mode were more ductile when the corbel had a/d = 1.5.

A summary on the characteristics of the literature concerned with the behavior of the RC corbels is depicted in Table A-1. It can be seen that the STM models was mostly design method adopted in designing the control specimens. Most studies reported that STM method is more adequate than the SF approach. Most of the variables that may affect the behavior of RC corbels including the strength of concrete, a/d ratio, ratio of the main steel, hoop reinforcement, etc. may be considered. Regarding the a/d ratio, most of the studies reported that this parameter was significantly influencing the behavior and mode of failure of the RC corbels. However, most of the tests were achieved with a/d<1.0 at which shear force is dominant. More tests are needed with 1.0 < a/d <2 at which the bending moment is dominant compared the shear force. For the type of concrete used in the tested corbels, it is clear that grade of concrete may affect the mode of failure. However, most studies considered the NSC (f'c<45 N/mm2). More studies need to be conducted on corbels with HSC, SFC, SCC and RPC to get deep insight on the response of the corbels made of ultra-high performance concrete (UHPC).

It is well known that the building construction may be subjected to various types of loading including static, dynamic, cyclic and repeated loading. However, most of the studies carried out on corbels considered the static loading. More studies need to be conducted on other types of loading to have more knowledge and clearer insight on the behavior of RC corbels under time dependent loads. Regarding the longitudinal reinforcement used in corbels, it was observed that most of researchers used the conventional ribbed steel reinforcement. However, few studies adopted the GFRP bars and the post-tensioned strands. Such studies revealed that these types of reinforcement might assist in development the behavior of the RC corbels. Then, the studies that consider the prestressing technique and using the reinforcing bars made of FRP composite (as GFRP, CFRP and BFRP) bars need to be extended and developed. Few studies were conducted considering the effect of the horizontal force on the response of the RC corbels. Such force was concluded to have a significant effect of the general behavior of the RC corbel. Then, more studies need to be conducted with values of a/d >1.0, high strength concrete or for corbels with FRP or post-tensioned main reinforcement. Studies on the segmented corbels need to be extended and developed to improve the knowledge about the segmental precast RC corbels.

Table 2 – Comparisons between Material used in EB Technique [50]

Property	**Steel Plate**	**FRP Sheet**	**FRP Plate**
Cost	Low	High	High
Bendability	Moderate	High; Corners need to be smoothed	Moderate
Installation	Easy	Need experience	Need experience
Resist./elevated temperature	High.	Sensitive	Sensitive
Environment durability	Affect by corrosion	Affected by salts	Affected by salts
Availability in market	Available	provided easily	Less available
fixing on concrete	drilled bolts / epoxy	epoxy	epoxy
Force to be resisted	All	Tension only	Tension and less comp.

4 Experimental and Theoretical Studied concerned the strengthening RC corbels

Strengthening is providing the structural element with additional resistance before cracking initiation. In some cases, like changes in function before use, design error, and degradation due to extreme weather conditions, the corbels need to be upgraded or strengthened. Thus, for effective performance, it is needed to upgrade corbels before the cracking stage (strengthening) or beyond cracking initiation (repairing) [50]. Several studies have been conducted during the past two decades that adopted various techniques of strengthening and repairing corbels including external bonding by steel or CFRP composites, near-surface installation technique NSM with CFRP or steel bars, prestressing, and adding steel sections. Regarding the external strengthening method, which is divided into three types, either by steel plate, FRP plate or FRP sheets. Table (2) shows the most important differences between types of external bonding strengthening techniques.

Various types of fibers have been developed to produce FRP materials. So, the fibers included carbon fibers (CFRP), glass (GFRP), and aramid (AFRP). The production of FRP in many shapes, like standard structural shapes, bars, 3D grids, 2D grids, or fabric, as illustrated in Fig. (14).

Fig. 14 – The Products of FRP in The Available Shapes (ISIS., 2007) [51]

Table 3 – Comparison between NSM FRP & NSM Steel Bars [50]

Property	NSM FRP	NSM steel bars
Cost	High	less cost
Bendability	Cannot be bent	Can be bent easily
Installation	Need experience	Need less experience
Fire-elevated temp.	Very sensitive to heat	Less sensitive
Failure mode	Deboning, less by rupture	Deboning, less by yielding
Force to be resisted	Tension only	All forces
Bond improvement	increasing bond length	using hook &anchorages

In many studies, it has been recently proposed to use the near-surface mounting (NSM) technique to overcome some of the external problems of strengthening. The CFRP bars were used in most NSM strengthening applications. Recently, the steel bars were used in place of the CFRP rods because of poor bendability and small resistance to compression and the high cost of CFRP rods. In contrast, the steel bar has good bendability, low price, and compression resistance. Table (3) shows the difference between the two methods. NSM systems consist of installing sheets or bars into the grooves that cut through the concrete surface and fixed in place with an adhesive.

4.1 Studies Concerned with Internal Strengthening

Fattuhi [52] has tested 32 specimens of corbels subjected to vertical loading. Six specimens were provided with horizontal stirrups as shear reinforcement. While, the steel fibers are used as shear reinforcement in the other 26 corbels. The parameters considered throughout the study were the ratio of main steel reinforcement, steel fiber content, and the shear-span/depth ratio. The results proved that a considerable improvement in ductility and strength of corbels when increasing the fiber content. The mode of failure may be changed from being diagonal splitting or shear to flexure.

Yang, et. al [53] have presented the test results of six double-sided, high-strength concrete corbels specimens. The main variables included the anchorage method of the main tension tie, the steel fibers percentage. It was found that when increasing steel fiber content, the load-carrying capabilities, ductility, stiffness, and crack width have all been enhanced. Moreover, it was reported that when using headed bars as the major “tension-tie reinforcement " rather than being fastened by welding to the transverse bars, good improvements in load-carrying capabilities, ductility, and stiffness were noticed.

Urban and Krawczyk [54] have conducted an experimental study that considered the post-installed threaded rods as an additional reinforcement to corbels. An increase in load-carrying capacity of up to 64% was obtained. Inclined and horizontal thread headed rods were used. The ratio of primary reinforcement was between 0.40 and 0.51%.

Kurtoglu [55] has proposed a support vector machine (SVM) based approach to estimate the ultimate load of RC corbels with steel or glass fibers. The SVM is an artificial intelligence-based method, which had been initially developed by Boser et al. (1992). The input parameters of this study were: fiber type (steel fiber and glass fiber), concrete tensile strength (ft), fiber volume ratio (Vf), yield stress of steel reinforcement (fy), grade of concrete (fcu), shear slenderness ratio (a/d), and the steel reinforcement ratio (ρ). The results showed that:

1. The proposed model showed high prediction for shear strength of both SFRC and GFRC simply supported corbels with various geometry and material properties.

2. The shear span/eff. depth ratio (a/d) has a dominant effect on the ultimate load capacity.

The behavior of high-strength reinforced concrete corbels with embedded W-rolled steel has been studied by Shakir [56]. The test included eight specimens with two shear span/depth ratios (0.70 and 1.00) with fc'= 57 N/mm2. The findings indicated that low-quality rolled steel in the market may be utilized in composite corbels and that such corbels might be used as a cost-effective alternative to traditional corbels. Furthermore, it had been discovered that the tested composite corbels resulted in higher ductility than the traditional ones, with values ranging from 120% to 170 %.

The response of composite corbels with embedded WT- rolled steel section with stiffened webs were considered by Shakir [57]. Corbels with shear span/effective depth ratios (a/d) of 0.70 and 1.0 were tested experimentally under gradually increased static loading up to failure. It was found that using the composite corbels with the proposed arrangement improved ductility and toughness by (35-80) % and (45-173) % respectively for a/d=0.70. For corbels with a/d=1.0, the enhancements were (38-101) % and (67-88) %. It was concluded that composite corbels with diagonal stirrups yielded the optimum response with relative recorded value for cracking and failure loads, ductility, and toughness for 82%, 98%, 105%, and 273% respectively for a/d=0.7. The respective values are 111%, 115%, 138% and 188% consecutively for a/d=1.0.

Shakir [58] has proposed a new modified arrangement for shear reinforcement in corbels. Inclined alignment of stirrups was studied. In addition, the performance of the model composite corbels was investigated. Twelve specimens were tested experimentally under vertical static concentrated loading system with two values of (a/d), which were 0.70 and 1.0. Four corbels are non-composite and eight are composite with two shapes of rolled steel, namely, WF and tapered WT sections. It was reported that the proposed configuration of shear reinforcement improved the ductility and toughness by 16% and 38%, respectively, for a/d value of 0.70, and 55% and 64%, respectively for an a/d value of 1.0, compared to the conventional arrangement. Furthermore, the results revealed that the ductility and toughness improved for the composite corbel with the proposed alignment by 35%–80% and 45%–173%, respectively, for a/d = 0.70 rather than RC corbel. The respective values for corbels with a/d = 1.0 were 38%–101% and 67%–88%, respectively.

4.2 Studies Concerned RC Corbels with External Strengthening

Irfan, et. al. [59] have used the carbon fiber-reinforced polymer sheets (CFRP) in strengthening the reinforced concrete corbels. Five specimens have been tested with shear slenderness ratio (a/d) equal to 0.8. The results showed slight improvements in failure load by (7 - 13)%.

Ozden and Atalay [60] have investigated experimentally the strength and post-peak performance of RC corbels, strengthened with externally bonded GFRP sheets with fc' of (23-26) N/mm2 and a/d < 1. Twenty-four RC corbels have been tested until failure. Several variables have been considered including the a/d ratio, quantity of main steel, and the number and configuration of GFRP sheets used. The results revealed that the strength of corbels with GFRP wrapping might be improved by 40% to 200% percent depending on the (a/d) ratio, corbel reinforcement ratio, and the configuration and number of layers of the strengthening material used. Wrapping with 45-degree orientation (diagonal) with regard to the corbel tension reinforcement yielded a higher degree of strengthening as compared to the horizontal wrapping. Moreover, higher load capacities may be obtained if the number of diagonally layers are increased. The mode of failure for wrappings parallel to the tension reinforcement of the corbel generally occurred with the strut failure.

Ahmad, et al. [61] have investigated the corbel shear behavior strengthened with carbon fibers reinforced polymer (CFRP). A total of twelve corbels had been tested up to failure. The theoretical values of the strut and tie forces obtained during the design of the corbels were also compared to the strut and tie forces obtained on the basis of load at the first shear crack and failure loads. It was concluded that:

1. Strut –and- Tie model provided a conservative estimate of the strength of the RC corbels. i.e., the RC corbels' experimental shear strength is over 100 % higher than the predicted shear strength calculated using the STM model.

2. The externally adhesive-bonded flexible CFRP can increase significantly, the ultimate shear strength of RC corbels.

3. CFRP increased the strength of the corbel beams up to 25%, which is less than that achieved by embedding steel reinforcement.

El-Maaddawy [62] has studied the structural behavior of RC corbels that were upgraded externally with CFRP. Nine specimen corbels have been tested, with f'c=41.5 N/mm2 and a/d ratio=1.1. Test variables included: the composition of the composite exterior panels and the amount of longitudinal internal reinforcement. External CFRP composite strengthening boosted loading capacity by up to 40%, while the addition CFRP sheets in the horizontal direction reduced steel stresses and improved the ultimate loads. The contribution of the externally bonded CFRP sheets to the ultimate load decreased with the increase in the amount of the internal steel bars. Diagonal CFRP sheets reduced the growth and expansion of shear cracks, thus increasing the load capacity. For corbels with main tensile steel only, a strength enhancement in the range of 21 to 40% has been obtained. Whereas, for corbels with main tension steel and horizontal stirrups, enhancements in strength of 15 to 33% were recorded.

Ivanova and Assih [63] have presented an experimental study for tracking the path of the cracks and crack growth in strengthened or repair RC short corbels with wrapped carbon fiber fabrics under static and dynamic loads. The results showed that strengthening of RC corbel bonded by CFRP might enhance the ultimate load to twice and stiffness less than a third. The success of strengthening depends strongly on surface preparation conditions. The results showed also that, the effect of fatigue on reinforced concrete short brackets, in a substantially lower tensile strength to 10 % relative to RC corbel load under monotone static test.

Mohammed and Hassan [64] have investigated experimentally the strengthening of high-strength concrete corbels using CFRP sheets with compressive strength (fc') ranging from 73.85 to 77.6 N/mm2. Twelve specimens had been tested with a/d=0.5. The results showed that there was an enhancement in load capacity when corbels have been strengthened with CFRP sheets with an optimum value of 28.3%. Results also indicated that the strengthened corbels suffered from high deformations before the collapse, and ductile behavior was observed for the whole load-deflection relationship. Steel and CFRP sheet materials suffered from high tensile strain, beyond the proportional limit, and before failure.

Neupane et. al. [65] have examined the adequacy of using the externally wrapped unidirectional CFRP sheet in treating poor detailing of the bearing pad over reinforced concrete corbels and compared its performance against traditional retrofitting methods. Eight corbel specimens were tested. Experimental results showed that the loading capacity of the damaged corbel due to the poor detailing of bearing pad position were not be fully recovered and the external CFRP wrapping method demonstrated superior performance over RC jacketing and was able to prevent localized failure. Further study based on non-linear 3D finite element analysis (FEA) commercial software called COM3D was carried out to identify the governing parameters of each retrofitting solution. It was concluded that:

1. The inadequate position of bearing pad where the bearing pad is placed at the edge of the RC corbel causes a significant drop in the loading capacity 46.5%, due to of local splitting failure. In order to investigate the residual capacity of the damaged corbel, the locally failed corbel (with inadequate position of bearing pad) was reloaded by moving the bearing pad to the designed position. Residual capacity of the damaged corbel was almost 95.5% of the corbel designed and detailed according to the ACI 318-11 code.

2. CFRP full wrap case showed a 92.02% capacity improvement better than CFRP wrap terminated at the column face that yielded improvements in range (61.44-81) %

Using the ANSYS computer program, Al-Fadhli, [66] has investigated the effect of using internal hybrid reinforcement (consisting of a combination of ordinary steel and CFRP bars) in concrete corbels, as well as the potential use of CFRP sheets for external strengthening. Then, compared the results to previous experimental results was discovered that using a combination of CFRP bars and ordinary steel bars to represent the main reinforcement in improving the ultimate load capacity of the corbels by 50 % When both CFRP bars and CFRP sheets were used together in the corbels.

Al-Kamaki, et al. [67] used the CFRP sheets as external strengthening for several RC corbels. Twelve RC corbel specimens were tested, six of which have been reinforced with horizontal stirrups and six without shear reinforcement. The parameters included: the amount of internal secondary steel bars and external composite sheets configurations. The results revealed that adding secondary reinforcement to corbels enhanced load capacity by up to 24%. Also, the diagonal CFRP scheme of strengthening improved the failure load of the corbel by 27 % of the reference specimen, compared to the horizontal configuration. The diagonal 45o CFRP reinforcement constrained widening and growth of the shear cracks.

Mohammad and Al-Shamaa, [68] have discussed the strengthening of RC corbels with average concrete strength of 63 N/mm2 and strengthened with NSM CFRP strips. Six corbels which were categorized into two groups, each of three specimens, were tested under static load. For each group, one corbel served as a reference specimen, two corbels in each category have been retrofitted with inclined and horizontal configurations as shown in Fig. (15). The main parameters are shear ratio (a/d), and orientation of CFRP. It was reported that for a/d =0.65, range of improvement in failure load by 10.3% and 15.45% for inclined and horizontal configurations respectively, has been obtained. While, for a/d =0.4, the range of improvement in failure load was 7% and 15% for the two alignments respectively. Furthermore, the mode of failure could be shifted from being of the brittle type to a more ductile one after strengthening.

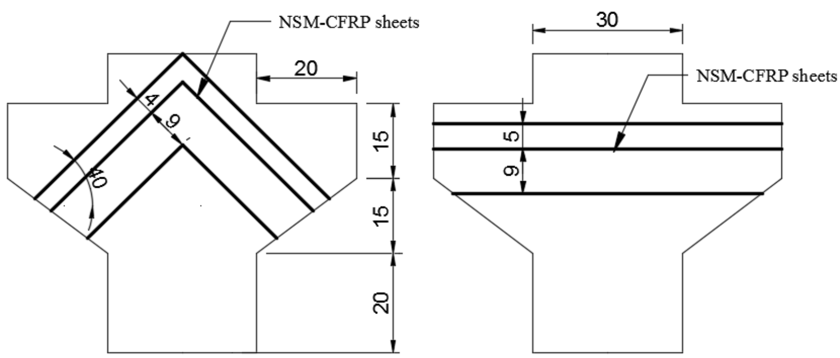


Fig. 15 – NSM-CFRP Position on Corbel [68]

Urban. et al [69] have studied experimentally the response of cracked loaded corbels upgraded by steel rods, Fig.(16), with (a/d) ratio ≈ 0.3. Three specimens had been tested with fcu=35.2 N/mm2. The ultimate load capacity of the strengthened corbel has been considerably enhanced by 40% higher than the control specimen. Also, it was observed that the capacity of the steel accessory mounted to the concrete column was 66% of the reference corbel.

Souza et. al. [70] have presented the results of the experimental tests of local repairing and strengthening a damaged reinforced concrete corbel of an industrial biomass boiler which was subjected to concrete spalling, favoring the risk of the main tie reinforcement slip in the anchorage zone. The main tie reinforcement was provided using vertical hooks. It was concluded that the proposed configuration was able to improve the strength and the ductility of the corbel by external wrapping (jacketing). Moreover, it was observed that the CFRP blanket has promoted the confinement of the concrete and avoided the spalling of the nib of the corbel, increasing the service life and durability. A Strut-and-Tie model based on the ACI-318 [17] was investigated using the package software CAST.

Zin et. al. ,2019 [71] conducted an experimental study to determine the influence of secondary reinforcement on the performance of corbels fabricated with three different types of high-performance fiber-reinforced cementitious composites, including engineered cementitious concrete (ECC); high-performance steel fiber-reinforced composite (HPSFRC); and hybrid fiber-reinforced composite (HyFRC). Two shear span-to-depth ratios (a/d = 0.75 and 1.0) are considered. It was shown that the SFRC corbel, among the other corbels, displayed the highest impact with 51% increment, followed by the ECC corbel with 45%, and lastly the HyFRC with 29% increment. Moreover, the ductility of the engineered cementitious concrete corbels for both a/d values improved in the range of (2 - 2.5) times, whereas SFRC corbels showed the greatest level of ductility, followed by HyFRC corbels. The strength increase of all cementitious composite corbels was compared. The secondary reinforcement improved the ultimate strength of 51%.

(a) Rods before embedded (b) corbel after strengthening

Fig. 16 – Rods Anchoring Accessory to Column [69]

The efficiency of strengthening of the high strength self-compacting RC corbels by EB CFRP sheets and near surface-mounted (NSM) steel bars has been studied by Shakir and Abdlsaheb [72]. Six specimens were tested, Fig. (17). One of which acts as a reference corbel and the other five are upgraded using the two methods with three configurations of alignment. Results revealed that the NSM steel bars technique could be adopted as an efficient and good method comparing to the external bounded EB CFRP technique. The enhancement in ultimate load capacity, relative to the control specimen were 95.1% and 91.6% for NSM technique with the inclined and horizontal alignment, respectively. Whereas, the corresponding enhancements using the CFRP sheet are 46.3% and 44.6%, respectively.

Table A-2 stipulates a summary for the characteristics of the research works conducted in the strengthening of the RC corbels. It can be observed that the most of studies concerned with NSC and HSC types of concrete. Few studies considered the RPC. Thus, more research works that considered the behavior of RC corbels made of RPC to extend the knowledge in this topic. More studies are necessary to consider the strengthening of the corbels made of the lightweight concrete (LWC). Moreover, most studies were carried out under systems of gradually increased static loading. Few studies considered the response under cyclic, repeated and dynamic loading. Furthermore, it is clear that the externally bonded CFRP sheets technique was the mostly used method. However, the test results of some studies concerned GFRP and BFRP sheets revealed that such materials might be adopted to develop efficient performance. Consequently, the studies on the strengthening of RC corbels should be extended to consider more FRP materials and technique as NSM steel bars. As well as, more variables and types of loading to be incorporated. Regarding the shear span ratio (a/d), it may be observed that the tests of the previous studies were conducted with a/d<1.0 . More experiments need to be performed on corbels tested under higher values of (a/d) to investigate the efficiency of the strengthening materials and technique when the bending moment is dominant.

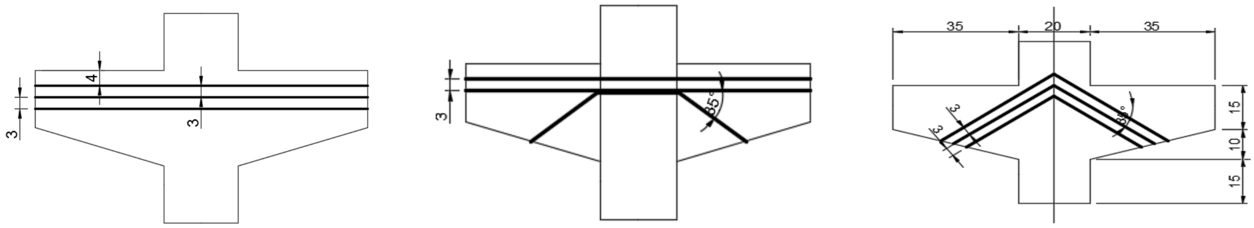
5 Experimental and Theoretical Studied concerned the repairing RC corbels

The strengthening of damaged reinforced concrete corbels by EB carbon fibre fabrics has been studied theoretically and experimentally by Assih, et al. [73]. Five RC corbels fcu=33 N/mm2 have been tested up to failure. Three of them were repaired at 45%, 65%, and 90 % of the failure load. It was concluded that the repair by the composite material contributed in increasing the ultimate load from 30% to over 50%. Mechanical damage up to 90 % has an effect on the ultimate load (less than 20 %). After being damaged, corbels failed either by shearing or splitting modes.

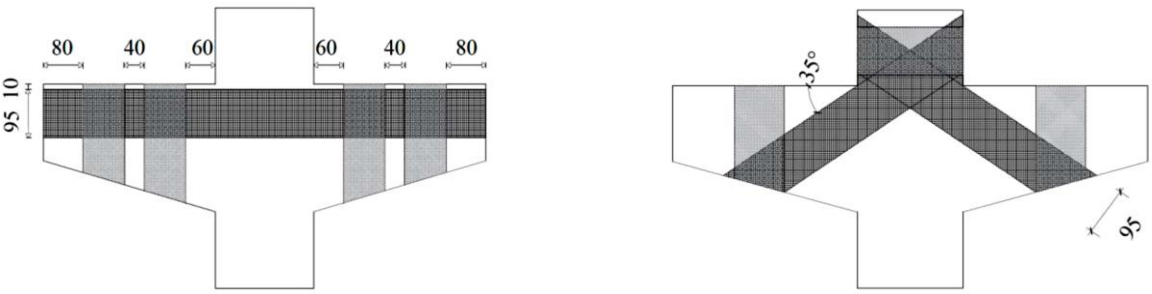
The behavior of reinforced concrete corbels damaged rehabilitated by basalt fiber fabric (BFF) has been investigated by Alshawaf, et al. [74]. The initial failure of the corbels was caused due to overloading after heating to various temperature levels (250oC, 500oC, and 750oC). The experimental work included testing nine specimens under vertical loading up to failure. Corbels were made of high-strength self-compacting concrete with fc' of 80 N/mm2 and a/d=0.69. Three amounts of steel fiber ratios (0%, 0.5%, 1%) were considered. It was concluded that the use of crack repair epoxy and basalt fiber fabric for the rehabilitation of corbel increases the ductility and load capacity. The existence of steel fiber improved the effectiveness of the rehabilitation due to partial restoration of the bridging effect of steel fibers. It is also concluded that the same stiffness value of corbels before rehabilitation is achieved after rehabilitation with basalt fiber fabric. Moreover, the existence of a high number of micro and macro cracks in damaged corbels decreases the effectiveness of the proposed rehabilitation technique, especially the enhancement in the load capacity.

Gulsan, et al. [75] have investigated the rehabilitation of the vibrated and self-compacted (SCC) steel fiber concrete (SFC) corbels with and without epoxy injection using basalt fiber mesh (BFM) and basalt fiber fabric (BFF). Sixty specimens were tested, 12 vibrated and 48 self-compacted. Several parameters were considered including type of concrete, values of a/d ratio, and the ratio of steel fiber. It was concluded that repairing with only epoxy injection is more efficient on corbels of moderate strength as compared to high-strength ones. Moreover, it was determined that using BFF to strengthen damaged RC corbels was a viable and powerful procedure.

Ivanova, et al. [76] have presented an analytical experimental study of retrofitting short RC corbels by external bonding of composite material (CFRP) under continuous load. Five short reinforced concrete corbels had been tested with a/d =0.45 and fcu (33,2 ±2) N/mm2. Two of them were tested under static test and three were tested under dynamic test by cyclic loading. The findings revealed that retrofitting approaches including composite material wrapping is a viable solution in the field of RC structures. Moreover, the ultimate load was improved by 14% relative to the control specimen.



(a) NSM steel bars configurations



(b) EB CFRP sheets configurations

Fig. 17 – Configurations of strengthening by NSM steel bars and EB CFRP sheets [72]

Repairing of the partially damaged high strength self-compacting RC corbels using NSM steel bars and EB CFRP sheets, has been investigated experimentally by Shakir and Abdlsaheb [77]. Same configurations shown in Fig (17) have been adopted. Eleven specimens were tested, one of which acted as a control corbel and the other ten are upgraded using several configurations with two damage levels (45% and 65%). It was concluded that the NSM steel bars technique might be adopted as an efficient method at the early levels of damage whereas the EB CFRP sheet is more suitable for the highly damaged corbels. Moreover, it was reported that NSM technique with the inclined, horizontal, and combined alignment yielded enhancements in ultimate load capacity of 98.6%, 55.1% and 74.2%, respectively for a damage level of 45% and 24%, 50% and 19% for damage level of 65%, respectively. Whereas, the corresponding improvement using the CFRP sheet with damage level of 45% are 52% and 50% for specimens repaired using horizontal and diagonal CFRP sheet, respectively. The respective values are 71%, 38% for damage level of 65%.

Table (A-3) shows the summary of studies conducted on the repairing of RC corbels. It can be observed that few knowledge is available about this topic. Many studies are needed that include different variables including a/d ratio, type of concrete, method and material of the rehabilitation, type of loading, effects of the elevated temperature, etc.

5 Conclusions

From the available review of literature on RC corbels, the following main points can be drawn:

1. Because that most of the cracks induced in short RC corbels follow vertical to the diagonal patterns, horizontal stirrups are employed in corbels rather than vertical stirrups.

2. Corbels subjected to repetitive loads fail in a similar manner to corbels tested under monotonic loads and within smaller levels of loading.

3. The load capacity of corbels may be reduced significantly when the corbel is subjected to horizontal load.

4. The failure load of corbels is significantly affected by the quantity of shear and flexure reinforcement, grade and type of concrete, and shear slenderness ratio (a/d).

5. The horizontal stirrups were effective such as the primary tension reinforcement in resisting vertical loads, but they were not as effective with combined-loading, so any contribution from the stirrups should be considered reserve strength. As a result, a minimum number of stirrups should always be available. Moreover, it was reported that vertical stirrups might be ineffective in improving the shear strength for corbels with (a/d ≤1).

6. Various types of fibers, such as polypropylene fibers or steel, or even plastic meshes, have been discovered to improve the properties of concrete corbels more effectively than conventional secondary reinforcement.

7. When steel fibers are present, the ultimate shear strength increases. Which the steel fibers reduced the crack widths in corbels.

8. The (STM) method has been found to be more accurate than the SF in estimating the capacity and behavior of RC corbels.

9. The ultimate shear strength increased with increasing the grade of concrete (f'c), the quantity of main reinforcement, and fiber content, whereas it reduced with the increase of the horizontal to vertical load ratio (Nu/Vu) and shear slenderness ratio (a/d).

10. In the instance of (a/d ≤1), horizontal stirrups are more efficient in improving the response of the RC corbels than vertical or inclined stirrups.

11. The secondary reinforcement improves ductility, reduces cracking width and, may change the mode of failure in corbels that fail under compression from being diagonal splitting to the mode of crushing of the compression strut.

12. Using the STM method was the sum of main and secondary reinforcements obtained was greater than the sum of main and secondary reinforcements acquired using the cantilever beam method.

13. Repairing and strengthening, using CFRP materials techniques, showed a significant improvement in the load-carrying capacity and behavior of the corbels.

14. Wrapping the carbon fiber fabric CFRP produced better good than applying it to the faces of the corbel when used in a horizontal configuration.

15. Few studies focused on structural behavior for concrete corbels repairing NSM steel bars and CFRP, which is an important step that could lead to new prospects for researchers and students interested in concrete corbels for strengthening with NSM steel bars.

16. Several parameters were considered including shear span to effective depth ratio (a/d), main and shear reinforcement ratio, grade of concrete, type of loading, corbel size and shape. Moreover, most of the previous experimental studies considered behavior of the RC corbels. Less number of studies interested with the strengthening issue. Few studies concerned with the repairing of the RC corbels.

Recommendations for future studies

The extensive survey of the literature conducted on the behavior, strengthening and repairing of RC corbels revealed that there are still many topics to be studied to improve the knowledge about the corbels elements. Some of these topics are listed below:

1. The proposed approaches to describe the behavior of RC corbels i.e. shear friction and STM models need to be extended to consider the composite steel-concrete corbels.

2. The repairing and rehabilitation of RC corbels need to be studied theoretically by STM approach to be used in evaluation the repairing of RC corbels within various levels of damage.

3. No study has considered the damage induced in the RC corbels under the effect of elevated temperature and the repairing of such members using different proposals and materials.

4. The effect of time-variations loadings as dynamic and seismic loads on the RC corbels need to be investigated.

5. The composite steel-lightweight RC corbels need to be studied under different types of loading.

6. The three and four sided connected to columns in two perpendicular planes need to be studded and the complicated case resulted from interaction between the stresses of corbels need to be investigated.

7. The behavior of the eccentrically loaded RC corbels may be studied to have better figure about the corbels when any imperfection occurred in loading.

8. It can be observed from this extensive review that most studies concerned with a/d values less than 1.0, More studies to be conducted on corbels with larger values of shear/depth ratio.

9. Corbels in crane and brides structures are affected by cyclic and reversal loadings. Thus, laboratory tests need to be conducted to determine the extent of effect of such types of loading.

10. Observations revealed that the formulations proposed in literature studied the analysis of the RC corbels. Consequently, more studies need to be done to establish formulations on the strengthening and repairing of corbels.

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A.1. Appendix : Characteristics of the studies concerned with the behavior of RC Corbels

Author	year	Design method	(a/d)	Concrete type	Loading type	others
Mattock et.al.	1976	SF[1]	0.45-1.0	NSC[3]	Static	H[7] Force
Clottey	1977	truss analogy	0.31-0.75	NSC	static	
Fattuhi, Hughes	1989	STM[2]	<1.0	SFC	Static	
Zeller,	1991	STM	0.5-1.0	NSC	Static	
Halabi,	1991	STM	0.1-0.6	HSC[4]	Static	
Hwang et. al.	2000	STM	0.1-0.68	NSC	Static	
Campione et.al.	2007	-----	<1.0	NSC-SFC	Static	
Rezaei et. al.	2011	SF &STM	-----	NSC	Static	H[7] Force
Salman et. al.	2014	STM	0.3-0.45	NSC-HSC	Static	
Fragomeni, R. Staden	2014	STM	-------	NSC-HSC	Static	
Al-Shaarbaf, Al-Azzawi	2015	-----	0.3-.7	NSC-HSC-SCC[5]	Static & repeated	
Abd Ghani	2015					
Lachowicz, Godycka	2016	------	0.3-0.6	NSC	Static	PT[8]
Abu Obaida	2016	STM	1-1.5	NSC	Static	GFRP[9] bars
Ridha et. al.	2017		0.4-0.8	UHPSFC[6]	Static	
Araújo, et. al.	2017	STM	<1.0	Hybrid	Static	Segmented
Ali, Mahdi	2017	------	0.37	NSC-HSC-SFC	Static	Hybrid
Putri,	2018	SF&STM	0.28	NSC	static	
Dawood,	2018	STM	0.3-0.45	NSC-HSC	Static	
Lacerda et.al.	2018	----	<0.5	NSC	Static	Grout filling
Chagas et. al.	2019	STM	0.7	NSC	Static	Segmented & PT[9]
Abdul-Razzaq, Dawood	2020	STM	0.5-1.5	NSC	Static	

Notes: 1)SF: Shear friction approach; 2)STM: Strut-and-tie models; 3)NSC: Normal strength concrete; 4)HSC: High strength concrete; 5)SCC: self-compacting concrete; 6)UHPSFC: ultra-high-performance steel fiber concrete; 7)H: horizontal; 8)PT: posttensioned; 9)GFRP: glass fiber reinforced polymers.

A.2. Appendix : Characteristics of the studies concerned with the Strengthening of RC Corbels

Author	Year	a/d	Type of concrete	Type of loading	Ex or In?	Type of Strengthening
Fattuhi	1990	<1	NSC[1]	Static	In[4]	Use of SFC
Erfan, et.al.	2010	<1	NSC	Static	Ex[5]	CFRP[7]sheets
Ozden and Atalay	2011	0.4-0.8	NSC	Static	Ex.	GFRP[8] sheets
Yang et.al.	2012	<1	HSC[2]	Static	Ex	Headed bars
Ahmad et.al.	2013	----	HSC	Static	Ex.	CFRP sheets
El-Maaddawy, El-Sayed	2014	1.0	NSC	Static	Ex	CFRP sheets
Ivanova and Assih	2015	0.45	NSC	Static & Dynamic	Ex	CFRP sheets
Mohammed, Hassan	2015	0.45	HSC	Static	Ex	CFRP sheets

Neupane,et.al.	2017	042+0.73*	NSC	Static	Ex	CFRP sheets
Urban, Krawczyk	2017	<1.0	NSC	Static	Ex	post-installed Threaded rods
Kurtoglu et. al.	2017	0.67-1.0	NSC	Static	Ex	GFRP sheets
Al-Fadhli	2017	0.75	NSC	Static	Ex	CFRP sheets
Al-Kamaki et. al.	2018	1.0	NSC	Static	Ex	CFRP sheets
Mohammad, Al-Shamaa	2018	0.65	RPC[3]	Static	NSM[6]	CFRP sheets
Urban et. al.	2018	0.3	NSC	Static	Ex.	Steel Accessory
Souza et. al.	2019	0.2	----	Static	Ex	CFRP sheets
Zin et. al.	2019	0.75, 1.0	HSC	Static	Ex.	HPSFRC[9] composites
Shakir	2020	0.7,1.0	HSC	Static	In	Composite sec.
Shakir	2021	0.7,1.0	HSC	Static	In	Composite sec.
Shakir	2021	0.7,1.0	HSC	Static	In	Composite sec.
Shakir&. Abdlsaheb	2022	0.9	HSC	Static	NSM Ex	Steel bars CFRP sheets

Notes: 1)NSC: Normal strength concrete; 2)HSC: High strength concrete; 3)RPC: reactive powder concrete; 4)In: internally installed; 5)Ex: externally bonded; 6)NSM: near surface mounted; 7)CFRP :carbon fiber reinforce polymers; 8)GFRP: glass fiber reinforced polymers; 9)HPSFRC: high-performance steel fiber-reinforced composite

A.3. Appendix : Characteristics of the studies concerned with the repairing of RC Corbels

Author	Year	a/d	Type of concrete	Initial loading	Type of repairing
Assih et. al.	2015	<1.0	NSC	Static	CFRP sheets
Alshawaf, Gülşan	2017	0.69	SC-SFRC	Thermal	BFF[1]
Gülşan,et.al.	2018	0.69	SC-SFRC	Static	BFF & BFM[2]
Ivanova et. al.	2019	0.45	NSC	Static & Cyclic	CFRP sheets
Shakir, Abdlsaheb	2022	0.9	HSC	Static	NSM-Steel bars CFRP sheets

Note: 1)BFF: Basalt fiber fabric 2)BFM: Basalt fiber mesh