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A Review of Previous Studies on the Reinforced Concrete Corbels

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Abstract: Corbels are short-hunched cantilevers that project from inner face of columns to support heavy concentrated loads or beam reactions. They are very important structural elements for supporting precast beams, girders and any other form of precast structure systems. ACI 318-14 provisions allow the structural design of shear-controlled corbels through either an empirical design method such as the shear-friction method or the strut-and-tie modeling (STM). This paper reviews some previous research studies on reinforced concrete corbels. From this literature; it was concluded that the STM method provides a more accurate estimation of ultimate load capacity and behavior than the shear-friction method. The ultimate shear strength increases with increasing main reinforcement, compressive strength ($f'c$), the presence of fibers, while it decreases with the increase of shear span-to- effective depth ratio (a/d) and horizontal to vertical load ratio (Nu/Vu).

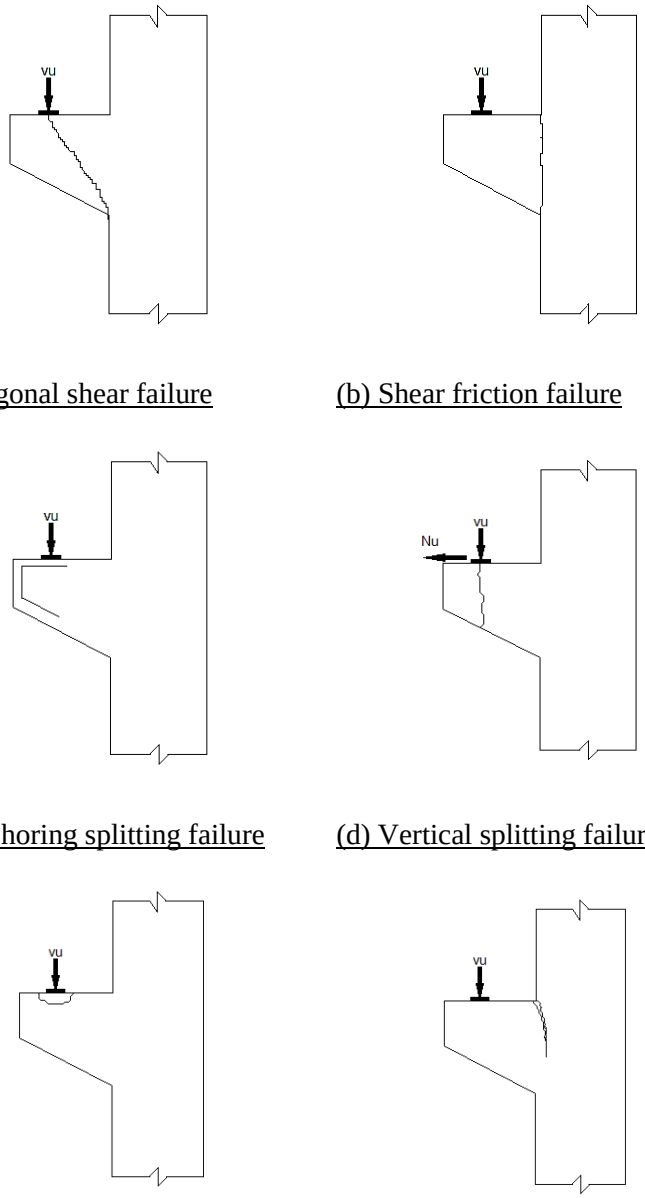
1. Introduction

According to ACI 318-14 [1], a/d is often less than 1.0. Such as small a/d ratio changes the state of stress of a member from a three dimensional into a two-dimensional one, i.e. state of plane stress as discussed in the case of deep beams. Shear deformations affect the behavior of corbels in the elastic stage and shear strength becomes the major factor according to shear friction, ACI 318-14, 22.9. On the other hand, ACI 318-14, chapter 23, STM can be used for the design of corbels with any a/d less than 2. Therefore, corbels with a/d less than 1 may be designed using either method. That is why this study is conducted to discuss the verification of STM versus shear friction approach in comparison with the experimental data took from the literature. Furthermore, discussing the effect of shear span to effective depth ratio (a/d), compressive strength ($f'c$), adding fiber (V_f), and the horizontal load to vertical load ratio on behavior and ultimate capacity of reinforced concrete corbels.

It is worth to demonstrate here the failure types in corbels [2]:

1- Diagonal shear failure: it starts from the point of concentrated load application and propagates toward the bottom corner junction of the bracket to the column face as shown in Figure 1(a).
2- Shear friction failure: it starts at the upper comer of the bracket or corbel and proceeds almost vertically through the corbel toward its lower fibers as shown in Figure 1(b).
3- Anchoring splitting failure: it occurs by rotating end of a freely supported beam as shown in Figure 1(c).
4- Vertical splitting failure: it usually happens by direct tension duo to horizontal load as shown in Figure 1(d).
5- Bearing failure: crushing of the concrete under the load-bearing, if the bearing area is not adequately proportioned as shown in Figure 1 (e).
6- Bending failure: main reinforcement yielding as shown in Figure 1 (f).

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

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

(e) Bearing failure (f) Bending failure

Figure 1. Reinforced concrete corbel failure modes

2. Previous Research Works

2.1 Strut and tie modeling versius shear friction method in corbels

Strut and tie modeling is developed as one of the most beneficial design approaches for critical shear structures. In STM, the Reinforced Concrete (RC) member is converted into an equivalent truss, where the tension and compression zones are transformed into equivalent ties and struts connected at the nodes to form a truss that resists the loadings [3-12].

In 1983, Hagberg [13] verified the application and evidence of the truss analogy. It was assumed that an intelligible model rather than empirical formulas provides the designer with a far better understanding of the transmission loads and of internal stress distribution. The derivations are based on earlier proposed design models which have been generalized to obtain explicit design formulas for tension versus compression failure. Based on that, it was concluded that:

1- The predicted values are safe, i.e., the specimens have generally higher test loads than the predicted capacity.
2- In particular, this is the case for specimens calculated to have a tension failure.
3- The observed yield loads are in very good agreement with the calculated yield loads.

In 2008, Yousif [14] used a simplified softened STM and nonlinear finite element analysis to study the behavior of reinforced high-strength concrete (HSC) corbels. To model the concrete material numerically, he used eight-node isoparametric plane stress elements. In modeling the concrete behavior, he used an elastic-strain hardening plasticity approach accompanied by cracking damage. The material of the steel rebars are treated as elastic-perfectly plastic and considered as embedded elements. The strut and tie moddeling of ACI 318-05 Code, Appendix A is followed [15]. Ultimate capacity predictions obtained by using both methods had good agreement with the test results of thirty-four corbels of the literature. The main concluding remarks are:

1- For the disturbed region analysis, the finite element modeling is effective.
2- For such as deep members, the simple truss analogy is reliable.
3- For optimum design, strut and tie modeling can be used together with the finite element method.

In 2015, Kassem [16] proposed a sturt and tie model to predict the ultimate capacity of reinforced concrete corbels. The proposed model is based on secant stiffness formulation, incorporating cracked concrete constitutive laws and strain compatibility. The proposed model evaluated the ultimate capacity based on the modes of failure accompinaed by diagonal strut splitting or crushing, crushing of nodes as well as longitudinal main reinforcement yielding. The ultimate capacity predicted by using the proposed model showed a better agreement with corbel test results of four hundred and fifty-five test results gotten from the available literature, than other available models. This proposed model provided more accurate predictions of ultimate capacity and behaviour than the approach of shear-friction certified by the ACI 318-11 [17], the STM provisions in different codes such as Australian, American, Canadian, New Zealand and Eurocode.

In 2018, Putri et al. [18] studied experimentally the behavior of corbels that designed with both shear friction and STM methods. The tests were implemented through two groups of specimens. Each group contained two specimens. The first group was designed by conventional shear friction method, while the second group designed by STM. The corbels were subjected to monotonic loading that increased up to failure, while the axial column was subjected to 50 kN fixed axial loading. It was concluded that:

1- The analytical and experimental results of the conventional shear friction method were 363.2 kN and 345.7 kN, respectively, while the analytical and experimental results of the STM were 306.9 kN and 299.4 kN, respectively.
2- Using conventional method, the shear capacity of specimens was 13.4 % more than that obtained by using STM. The shear capacity for each STM and conventional methods were 1.67% and 1.92% more than designated load, respectively.

In 2018, Khosravikia et al. [19] evaluated the behavior of reinforced concrete corbels designed according to the STM provisions of AASHTO LRFD [20]. To do so, first, the performance of three full-scale corbel specimens designed according to STM were experimentally evaluated as shown in Figure 2 and Figure 3. Then, an experimentally validated nonlinear finite-element models were used to investigate the crack-control reinforcement requirements for RC corbels. The results from the experimental study indicated that:

1- The STM provisions of the AASHTO LRFD provide conservative estimates of the load carrying capacity of RC corbels. Though, examination of the smeared node near the corbel-column interface, a check not currently required in AASHTO LRFD, is highly recommended.
2- The results from the numerical study suggest that a reduction in the amount of secondary reinforcement currently required by AASHTO LRFD may be feasible, depending on the reinforcement layout used.

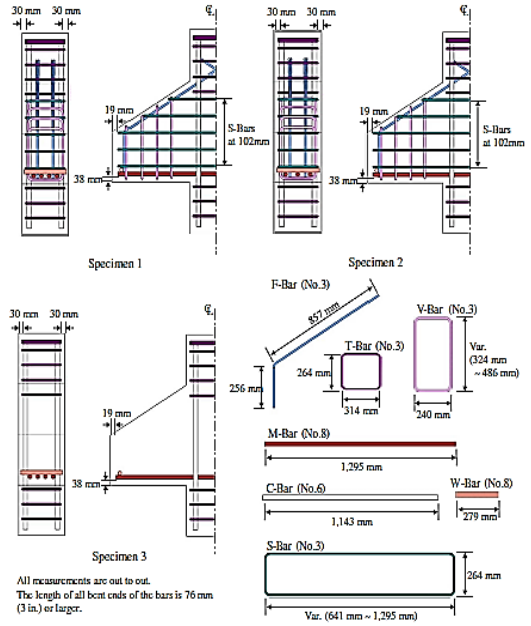


Figure 2. Reinforcement details, Khosravikia, et al. (2018) [18].

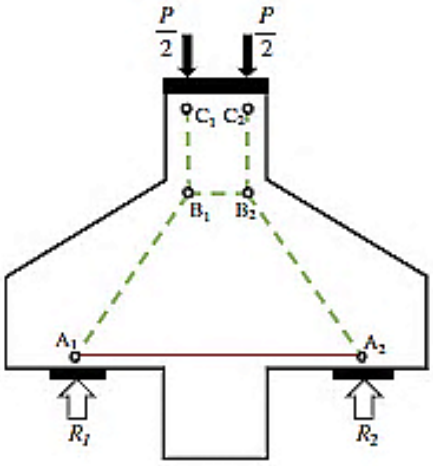


Figure 3. Strut-and-tie model, Khosravikia, et al. (2018) [18].

2.2 The effect of shear span-depth ratio a/d

In 1976, Mattok et al. [21] studied the behavior of reinforced concrete corbels by the shear-friction method of corbels having a/d up to 1.0, subjected to combinations of horizontal and vertical loads. By the experimental test of Twenty-eight corbel specimens, it has already been shown that the simultaneous action of a moment equal to the flexural ultimate strength of a cracked section does not reduce the shear which can be transferred across the crack. Therefore, the arbitrary limitation of the shear-friction design method used in cases when a/d < 0.5 is unwarranted. Twenty-six of those specimens contained horizontal stirrup reinforcement. The main conclusions were:

1- The maximum shear stress attainable decreased as a/d increased.

2- The failure at larger values of a/d occurs by shear compression of the concrete before the yield of both the main tension reinforcement and the stirrup reinforcement.

In 2000, Hwang et al. [22] proposed a softened STM to determine corbel shear strength. The proposed model was created based on the concepts of the STM and satisfies compatibility and equilibrium. The proposed model shear strength predictions in addition to the ACI 318 -95 [23] empirical formulas were compared with experimentally collected data of one hundred and seventy-eight corbels. It was seen that the softened STM showed better performance than the ACI 318-95 [17] approach for all the comparison parameters. According to the proposed model, the following conclusions were drawn:

1- The vertical and horizontal stirrups are taken to be equally effective in strength resistance at a/jd = 1, where jd is lever arm from centroid of primary tension steel to compressive force resultant.
2- The horizontal reinforcement is insignificant in the shear-carrying capacity for corbels with a/d = 1.
3- When a/d ≤ 1, the vertical stirrups are not effective for shear strength.
4- In the softened STM, the vertical stirrup can restrain the cracks in the horizontal direction.
5- For the concern of durability associated with crack control, it is recommended that the vertical stirrup is detailed within the corbels with a/d ≥ 0.5.

In 2012, Yang and Ashour [24] studied the prediction of the reinforced concrete corbel shear capacity using mechanism analysis. According to the shear failure seen in experimental tests, kinematical mechanism admissible failure is idealized as an assemblage of two rigid blocks separated by a displacement discontinuity failure plane as shown in Figure 4. Predictions of shear capacity determined

from the developed analysis mechanism are closer to the experimental corbel test results of literature than other available models of corbels. The proposed model showed that the corbel shear capacity generally increases with decreasing a/d.

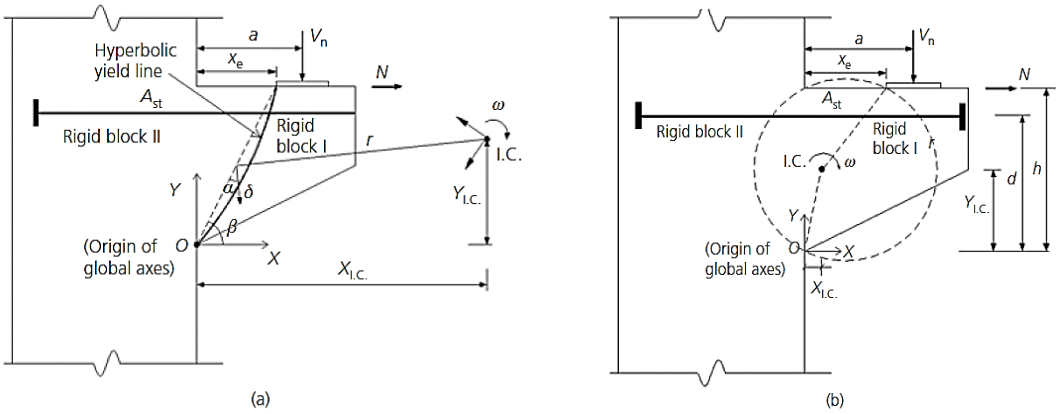


Figure 4. Idealized failure mechanism of corbels: (a) hyperbolic yield line; (b) yield line with two straight segments, Yang and Ashour (2012). [24]

2.3 Effect of compressive strength

In 1994, Yong [25] investigated experimentally the behavior of corbels made with 40 MPa HSC. A total of sixteen full-size corbels were tested, two of them were unreinforced. The primary investigation variables were reinforcement ratio, the existence of horizontal force, and the ratio of a/d. High-range water-reducing admixtures and silica-fume were used to get the HSC. In all cases but one, the main steel reinforcement yielded before failure. The corbel behavior throughout testing and the analysis of results showed that:

1- Increasing the *f'c* leads to increase corbel ultimate capacity, but does not lead to brittle failure. Increasing the reinforcement ratio also an increases the strength capacity. Based on the ratios of tested reinforcement, the reinforcement increase does not lead to increase the failure ductility.
2- The behavior of HSC corbels is similar to that of NSC corbels. The concrete strength increase does not negatively affect the corbel ductility.
3- Comparing with the procedure of the American Concrete Institute, the truss analogy model presented accurate strength predictions.
4- The code limitation of 5.5 MPa (800 psi) for maximum average shear stress confines the full use of the HSC corbel available shear strength.

In 1996, Foster et al. [26] tested thirty corbels under vertical loading. The main test variables were concrete strength which was 45 to 105 MPa, a/d, and the secondary reinforcement provision. These conclusions were drawn based on the test results:

1- The first cracks are flexural ones initiating from the intersection of column and corbol. The flexural cracking load increases with decreasing a/d.
2- HSC Corbels behaved similarly to NSC corbels.
3- Providing secondary reinforcement enhance ductility, reduces crack widths, and may change the mode of failure from diagonal splitting to strut compression crushing for beams that fail in compression. A horizontal stirrup minimum amount similar to that for NSC corbels should be used in HSC.
4- The plastic truss model provides a good tool for designing HSC corbels.

In 2010, Aziz and Othman [27] studied experimentally the ultimate shear strength of HSC corbels under vertical loads. The experimental program consisted of casting and testing fourteen HSC corbel specimens of 40 to 60 MPa with main reinforcement ratios of 0.517 %, 0.776% and 1.034 %, shear reinforcement stress ρ_{hfyh} was 1.535, 2.305 and 3.071 MPa. The outside depth to the total depth ratio (k/h) was 0.24 to 1.00. It was concluded that:

1- The behavior of HSC corbels are similar to those made with NSC. Increasing *f'c* increases the ultimate capacity of corbel but does not cause brittle failure.
2- By increasing the *f'c* of concrete, the ultimate capacity by means of ductile failure increases.
3- The ultimate capacity increases by about 21% and 28%, by increasing *f'c* from 40 to 62 MPa for ρ_{hfyh} equal to 1.535 MPa and 2.305 MPa, respectively.
4- The horizontal reinforcement contribution in increasing ultimate capacity is more effective for *f'c* = 62 MPa corbels.

In 2014, Salman et al. [28] studied experimentally the behavior of NC and HS of SCC. The program included ten specimens, in which the ratio a/d, steel fiber (V_f) amount, and *f'c* were varied. All specimens had the same main reinforcement and dimensions. They all were under concentrated vertical loading only. According to the results, it was concluded that:

1- The increase in f'c decreases deflection values.
2- With increasing f'c by approximately 93%, the cracking load and ultimate load improve by about 29% - 46% and 52% - 71% for normal strength self-compacting concrete (NSCC) and high strength self-compacting concrete (HSCC), respectively.
3- Due to presence of steel fibers, the improvement in the cracking capacity of self-compacting reinforced concrete corbels is larger than the improvement caused by increasing f'c.

In 2015, Al-Shaarbaf et al. [29] investigated experimentlly the behavior of reinforced concrete corbels under repeated vertical loadings by casting and testing twenty-four vibrated and SCC corbels with NC and HSC. All corbels had the same main reinforcement. Twelve of these specimens were subjected to monotonic loading until failure with different a/d, amounts of the horizontal stirrups, strength values of concrete including NC and HSC and the types of concrete including vibrated and SCC. It was concluded from the results that the horizontal stirrups have an insignificant effect on cracking and ultimate loads of corbels with HSC as compared with NSC.

2.4 Effect of adding fiber

In 1990, Fattuhi [30] tested thirty-two reinforced concrete corbels under vertical loads. Steel fibers are added to concrete as reinforcement for shear in twenty-six corbels. The main parameters varied were the volumes of traditional bar reinforcement and fibrous reinforcement in addition to a/d ratio. It was concluded that:

1- As the fiber content was increased, significant enhancement took place in strength and ductility of corbels.
2- In some cases, it was possible to vary the failure mode from being shear or diagonal splitting to flexure.
3- An empirical equation, equation (1), is offered for estimating the corbel shear strength:

$$V_n = k_1 bh(f_{ct})^{k_2}\left(\frac{a}{h}\right)^{k_3}\left(\frac{f_y}{f_{cu}}\right)^{k_4}\left(\frac{d}{h}\right)^{k_5}(\rho)^{k_6} \quad (1)$$

where *Vn* is the corbel nominal shear strength, and k_1 to k_6 are constants. Their values k_1 = 57.292, k_2 = 0.315, k_3 = -0.812, k_4 = -0.049, k_5 = 0.678, k_6 = 0.626 were obtained from regression analysis using Lotus 1-2-3 package.

4- Comparison between the calculated shear and experimental strengths of all tested corbels presented that the obtained two values in each case are close to each other.

In 2012, Khalifa [31] studied a macro-mechanical STM for analysis of fibrous HSC corbels. In that model, the fibers were used as a horizontal stirrup reinforcement replacement, due to the idea of increasing shear friction for fiber high strength concnrete (FHSC). The analytical macro-mechanical model took into consideration the effect of volume of fibers, length of fibers, the diameter of the fiber, fiber random distribution, FHSC interface, and a/d ratio. From the stuided model, it was concluded that:

1- The fibers can be added to concrete as a full or partial replacement for the horizontal stirrups, due to shear friction increasing for the FHSC.

2- The fiber volume fraction effect on the maximum vertical load capacity applied on corbels is decreased with decreasing the volume of fiber fraction.
3- Recommending increasing fiber aspect ratio and/or fiber volume rather than increase *f'c* more than 50 MPa.

In 2012, Abdel Hafez et al. [32] studied experimentally the shear behaviour of high strength fiber reinforced concrete corbels without and with fibers. Seventeen HSC corbels were tested. The test variables were V_f, a/d, cube concrete strength (fcu), main steel reinforcement area and existence of horizontal stirrups. From the test results, increasing fiber contents from 0% to 1.0% and then to 1.5% results in improving:

1- Ultimate capacity by about 19%.
2- Tested corbel ductility, and leads to a more ductile failure mode, in addition, to increase the number of diagonal cracks.
3- Stiffness.

In 2012, Mohamad-Ali and Attiya [33] investigated experimentally the effect of carbon fibre reinforced polymer (CFRP) strips on the ultimate capacity and behaviour of repaired and strengthened concrete corbels. The variables of the experimental program included direction, location, CFRP amount and a/d ratio effect on the strengthened corbel behaviour. All corbels had the same flexural reinforcement and dimensions. They were with no horizontal steel shear reinforcement. The experimental results gotten from the repairing and strengthening CFRP techniques presented:

1- The carrying capacity and behaviour of the tested corbels improved.
2- The ultimate capacity had been gotten for specimens strengthened by inclined technique increased about (44.5 - 60) % with compared to the ultimate capacity of reference corbel and (14.7 - 31.2)% for specimens strengthened by the horizontal technique as shown in Figure 5.
3- An increase of 56% related to the ultimate capacity of reference corbel is reached for corbels repaired with the strips of CFRP.
4- The strengthened corbels showed the stiffer response of load-deflection than relating reference corbels, i.e. corbels which are not strengthened.

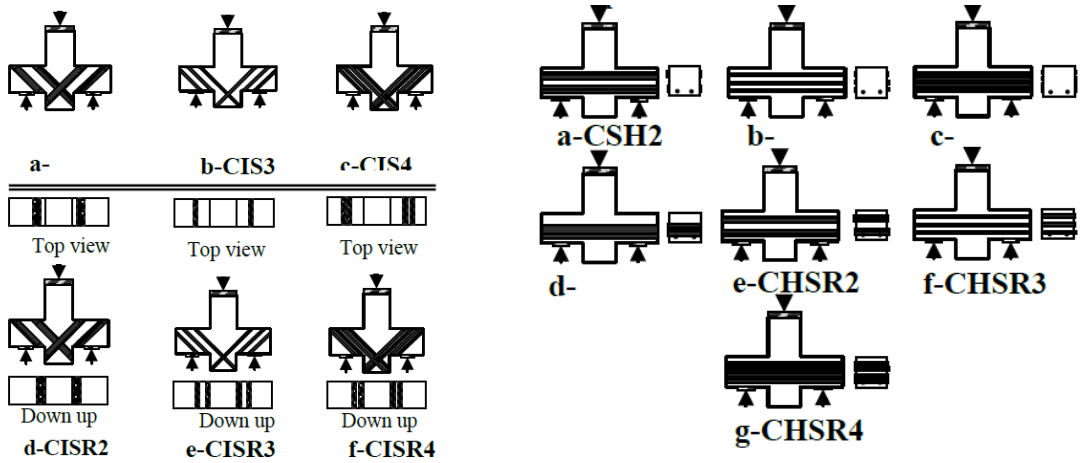


Figure 5. Dimensions and reinforcement details, Mohamad-Ali and Attiya (2012). [33]

2.5 The effect of horizontal load to vertical load ratio

In 1965, Kriz and Raths [2] studied experimentally and theoretically the strength of corbels by testing one hundred and twenty-four corbels. Half of the corbels were under vertical loads only. The second half was under combined horizontal and vertical loads. It was concluded from the test results that:

1- Horizontal forces acting outward from the column significantly reduce corbel strength as shown in Figure 6 and Figure 7. These horizontal forces must be taken into considerations in the design except special provisions for unrestricted movements of the supported beams.

2- The stirrups did not enhance the ultimate capacity of a corbel under combined loading by a large proportion as was the case with a corbel under vertical loads only. Thus, it was concluded that a minimum amount of stirrups must permanently be added.

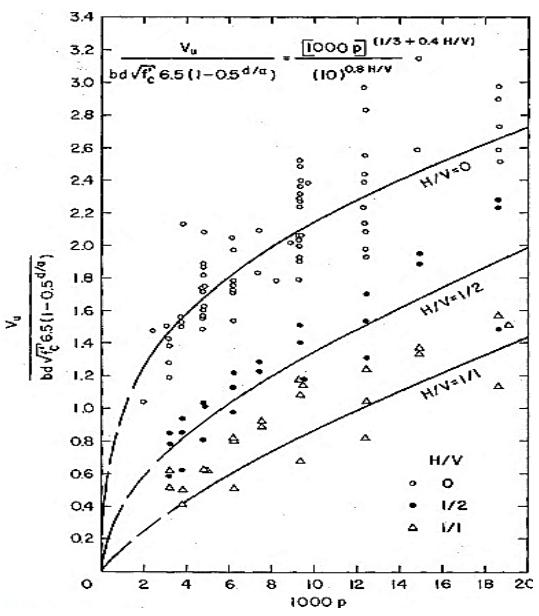


Figure 6. Ultimate capacity of corbels, Kriz and Raths (1965). [2]

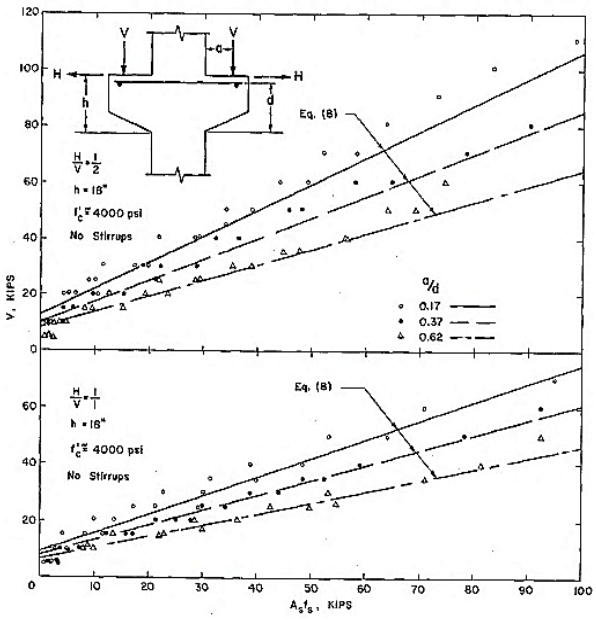


Figure 7. Relationship between applied load and tension steel force, combined vertical and horizontal loading, Kriz and Raths (1965). [2]

In 1976, Mattok et al. [21] studied the behavior of reinforced concrete corbels under both horizontal and vertical loads such that horizontal to vertical load ratio (Nu/Vu) < 1.0 by the experimental test of twenty-eight corbel specimens. Twenty-six of them contained horizontal stirrup reinforcement. From the test results, two types of cracks were caused by the horizontal forces, more specifically:

1- More vertical cracks produced in the concrete by the horizontal force due to the direct tension stresses.
2- Cracks approximately aligned with the main tension reinforcement and evidently caused by the splitting action of the bar deformations due to the high bond stresses. These high bond stresses are caused by the transfer of some of the horizontal forces from the main tension reinforcement to the surrounding concrete.

In 2011, Rezaei et al. [35] studied the effect of primary and secondary reinforcements in corbels subjected to the combined action of horizontal and vertical loadings. Two different methods, cantilever beam method and STM proposed by the ACI 318-11 have been used to determine secondary and primary reinforcements. From the obtained results, it was concluded that:

1- The amount of primary and secondary reinforcements obtained by using STM is more than the corresponding amount provided by the cantilever beam method.
2- As per the STM, the cross-sectional area of secondary reinforcement is considerably larger in the presence of a horizontal load.
3- When 20% or less of vertical load is included, the method of the cantilever beam is appropriate.
4- In the case of applying a horizontal load, the ultimate vertical load carrying capacity decreases significantly.

3. Concluding Remarks

1- Strut and tie modeling provides more accurate estimation of ultimate capacity and behavior than the shear-friction method.

2- Generally, the ultimate shear capacity of corbels increases with decreasing a/d ratio.
3- In case of a/d ≤ 1, horizontal stirrups are more effective in enhancing the reinforced concrete corbel behavior than vertical or inclined stirrups.
4- Providing secondary reinforcement decreases crack widths, enhances ductility, and for beams that fail in compression, may convert the mode of failure from diagonal splitting into strut compression crushing.
5- The horizontal stirrups have an insignificant effect on cracking and ultimate loads of corbels with HSC as compared with NSC.
6- The behavior of HSC corbels are similar to those made with NSC.
7- The maximum potential of HSC may not be realized in reinforced concrete corbels due to the brittleness of the materials.
8- The improvement in the cracking capacity of self-compacting reinforced concrete corbels due to the presence of steel fibers is larger than the improvement caused by increasing the concrete *f'c*.
9- The presence of horizontal loads increases vertical cracks due to direct tension stresses.
10- The amount of primary and secondary reinforcements obtained by using the STM method is more than the corresponding amount provided by the cantilever beam method.

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