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STRENGTH OF REINFORCED CONCRETE CORBELS – A PARAMETRIC STUDY

Asala Asaad Dawood
M.Sc. Student/University of Diyala/College of Engineering/ Department of Civil Engineering

Ali Kifah Kadhum
Assistant Lecturer /University of AL-Mustansiriyah /College of Engineering/ Department of Civil Engineering

Khattab Saleem Abdul-Razzaq
Prof. Dr. /University of Diyala/College of Engineering, Department of Civil Engineering

ABSTRACT

Corbels are cantilever with small shear span to depth ratio (a/d) projected from columns or walls to support precast members like beams, girders or dapped end beams. Shear friction (SF) method is used to analyze and design reinforced concrete (RC) corbels. Because of the small value of a/d, corbels are treated as deep beams. Using strut and tie modeling (STM), they can be analyzed. In both SF and STM, there are many parameters that affect the behavior of the corbels such as a/d, width (b), compressive strength of concrete (f'c), yield strength of reinforcement (fy), and horizontal to vertical load ratio (H/V). In the current study, according to ACI 318-14 provisions, the effect of these parameters were investigated using both SF and STM. It was found that the shear capacity increases by about 32.6%, 26.3% and 31.2% for SF and by about 54.1%, 50.4% and 30.9% for STM with increasing width, compressive strength, and yield strength by about (100-300) %, (15-35) % and (400-600) %, respectively. Whereas, shear capacity decreases by about 58.54% and 48.7% for SF and about 59.4% and 33.2% for STM with increasing a/d and H/V by about (0.1-1.9)% and (0-1)%, respectively. It was also seen that the results obtained by STM is more reliable than SF when compared with experimental works that were taken from literature.

Keywords: Reinforced Concrete, Corbels, STM, Shear friction, flexure, strength, Parameter.

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1. INTRODUCTION

Brackets and corbels are short cantilevers that may fail by shearing along the interface between the column and the corbel, yielding of the tension tie, crushing or splitting of the compression strut, or localized bearing or shearing failure under the loading plate [1]. According to ACI 318-14 [2], there are two methods to analyze and design reinforced concrete corbels; SF, ACI 318-14, 22.9 and STM, ACI 318-14, chapter 23. SF method should be used for corbels with a/d ≤ 1.0 and H ≤ V, while STM can be used for corbels with a/d < 2 [3, 4].

In the current study, both SF and STM approaches are used to investigate the behavior of RC corbels with different values of a/d, b, *f'c*, *fy*, and H/V.

2. ANALYSIS OF CORBEL

2.1. Shear friction theory (SF)

The shear friction analogy is familiar to most engineers in practice and to most researchers in investigations [5-7]. It is a valuable and simple tool which can be used to estimate the maximum shear force transmitted across a cracked plane in a reinforced concrete member, Fig.1. It is used for the design of short corbels wherein a control of the interface stresses is necessary to prevent a possible shear failure. More specifically, it is used with precast concrete structural connections for estimating the shear capacity of interfaces between precast members and cast-in-place concrete. In addition, it is used for calculating the residual shear capacity of cross sections which are weakened by cracking.

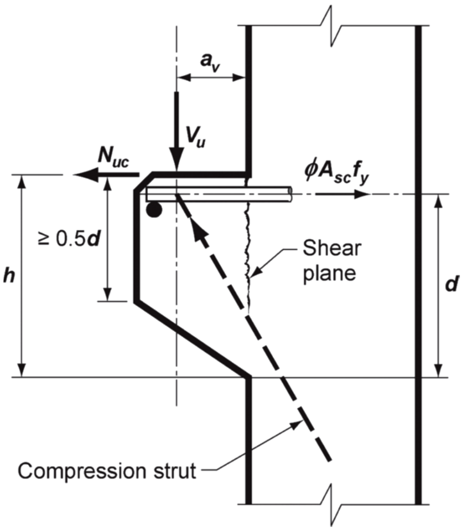


Figure 1 Shear Friction Analogy

Using SF can be summarized by the following steps:

1-Flexure reinforcement:

$V_n = \frac{Mn}{a} * 10^3$

Where:

$M_n = As*fy*(d-\frac{a}{2})* 10^{-6}$

$a = \frac{\rho * fy * d}{0.85 * f'c}$

$\rho = \frac{As}{bd}$

2-Shear friction reinforcement:

$V_n = \mu A_{vf} fy$

3-Minimum reinforcement:

$V_n = 0.04\ (f'c\ /fy)\ (bd)$

4- Check overall dimensions:

V_n is minimum of:

(a) For normal concrete, the minimum of the following values:

$0.2 * f'c * b * d$

$(\ 3.3 + 0.08 f'c)\ b * d$

$11bd$

(b) For high strength concrete, the minimum of the following values:

$0.2 f'c * b * d$

$5.5bd$

5- Check for bearing:

$V_n = 0.85 f'c * b * L_b$

6- Find shear capacity by select minimum of V_n

2.2. Strut and tie modeling (STM)

Strut and tie modeling is developed as one of the most beneficial design approaches for critical shear structures [8-12]. In STM, the 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, Fig.2.

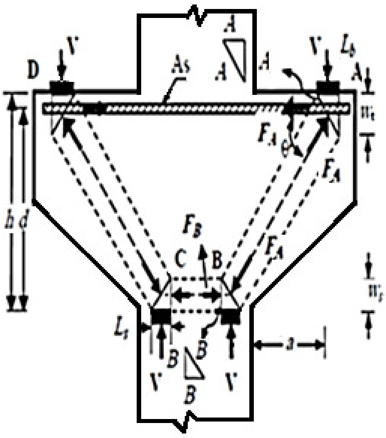


Figure.2: Strut and Tie Modelling

Using STM can be summarized by the following steps:

1- Find node dimension

$w_t = 2*(h-d)$, $w_s = 0.8*w_t$

$jd = h - 0.5*w_t - 0.5*w_s$

$\theta = tan^{-1}\left(\frac{jd}{a+\frac{Ls}{2}}\right)$

$w_{sb} = Ls\ \sin\theta + w_t \cos\theta$

$w_{st} = L_b \sin\theta + w_s \cos\theta$

2- Find shear force at nodal zone A, CCT, Fig. 3-1.

$\beta s = 0.8, f_{ce} = 0.85\beta s * f'c$

$V_{n,A1} = f_{ce} * L_s * b$

$V_{n,A2} = f_{ce} * w_t * b * \tan\theta$

$V_{n,A3} = f_{ce} * w_{sb} * b * \sin\theta$

3- Find shear force at nodal zone B, CCC, Fig. 3-2.

$\beta s = 1.0, f_{ce} = 0.85\beta s * f'c$

$V_{n,B1} = f_{ce} * L_b * b$

$V_{n,B2} = f_{ce} * w_s * b * \tan\theta$

$V_{n,B3} = f_{ce} * w_{st} * b * \sin\theta$

4- Find shear force at Strut AB, bottle shaped

$Q = \sum(Asi/bi*si)*\sin\alpha i$, Fig. 3-3

If $Q \geq 0.03$, $\beta s = 0.75$

If $Q < 0.03$, $\beta s = 0.6\lambda$

$\lambda = 1.8173\left(\frac{fct}{\sqrt{f'c}}\right) - 0.0143$

$f_{ce} = 0.85\beta s * f'c$

$w_{eff} = \min(w_{st}; w_{sb})$

$V_{n,AB} = f_{ce} * w_{eff} * b * \sin\theta$

4- Find shear force at Strut BC, prismatic shape

$\beta s = 1.0, f_{ce} = 0.85\beta s * f'c$

$V_{n,B2} = f_{ce} * w_s * b * \tan\theta$

5- Find shear force at Tie AD

$F_{n,AD} = As\ fy$

$V_{n,AD} = Fn,AD * \tan\theta$

6- Find maximum nominal shear

$V_{n.\ max} = 0.83*b*d*\sqrt{f'c}$

Then

$V_n = \min(V_{n,B1}; V_{n,B2}; V_{n,B3}; V_{n,A1}; V_{n,A2}; V_{n,A3}; V_{n,AB}; V_{n,BC}; V_{n,AD}; V_{n.\ max})$

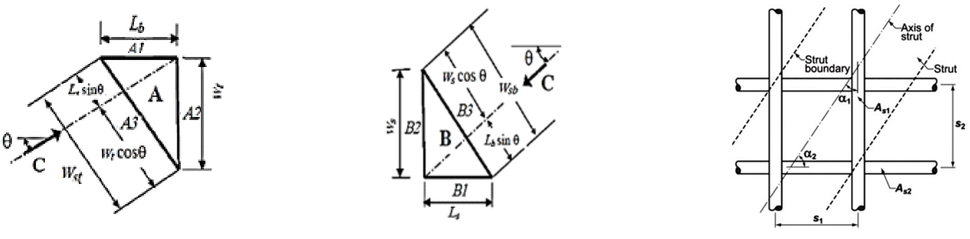


Figure 3-1: Node A

Figure. 3-2: Node B

Figure. 3-3:secondry reinforcement

Figure.3: STM details

3. DESCRIPTION OF THE SPECIMENS

Double reinforced concrete corbel specimens to investigate the parameters that affect its shear capacity as shown in Fig.4, a=360.5mm, d=360.5mm, b=120mm, as=452.4mm2, Ah=226.2mm2, *f'c*=25MPa, *fy*=420MPa, L_b=90mm and L_s=90mm. The parameters that taken into considerations are a/d, b, *f'c*, *fy* and H/V. According to ACI 318-14 [1], SF and STM methods are used.

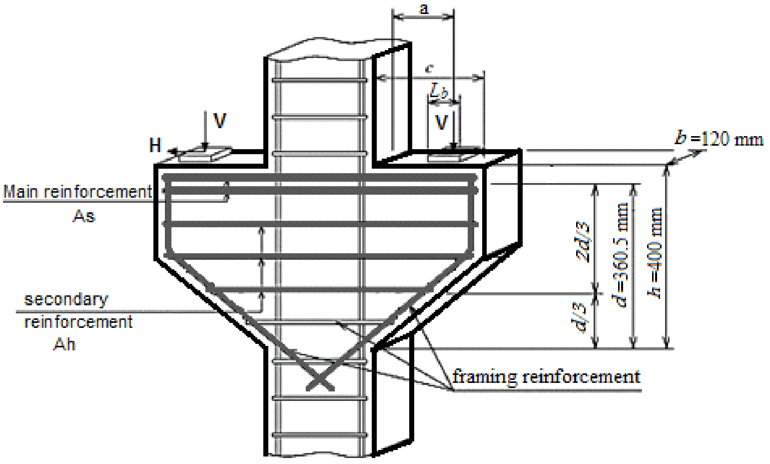


Figure 4: Typical RC Corbel Specimen

4 PARAMETRIC STUDY

4.1. Effect of a/d

The shear failure is mainly dependent on a/d ratio, therefor, it's considered the most important parameter. In the current study, a/d are ranged between 0.1 and 1.9 as shown in Table 1 and Fig. 5.

Table 1: Effect of a/d

a/d	Shear Friction		STM	
	V_n-SF kN	Failure mode	V_n-STM kN	Failure mode
0.1	216.3	S	179.53	DS
0.2	216.3	S	179.53	DS
0.3	216.3	S	179.53	DS
0.4	216.3	S	179.53	DS
0.5	216.3	S	173.52	CS
0.6	216.3	S	164.39	CS
0.7	216.3	S	154.84	CS
0.8	212.96	F	145.32	CS
0.9	189.30	F	136.13	CS
1	170.37	F	127.44	CS
1.1	154.88	F	119.33	CS
1.2	141.98	F	110.98	CS
1.3	131.05	F	103.19	CS
1.4	121.69	F	96.43	CS
1.5	113.58	F	90.49	CS
1.6	106.48	F	85.25	CS
1.7	100.22	F	80.57	CS
1.8	94.65	F	76.39	CS
1.9	89.67	F	72.62	CS

where S=shear, F = flexural, DS =diagonal shear and CS = strut compression

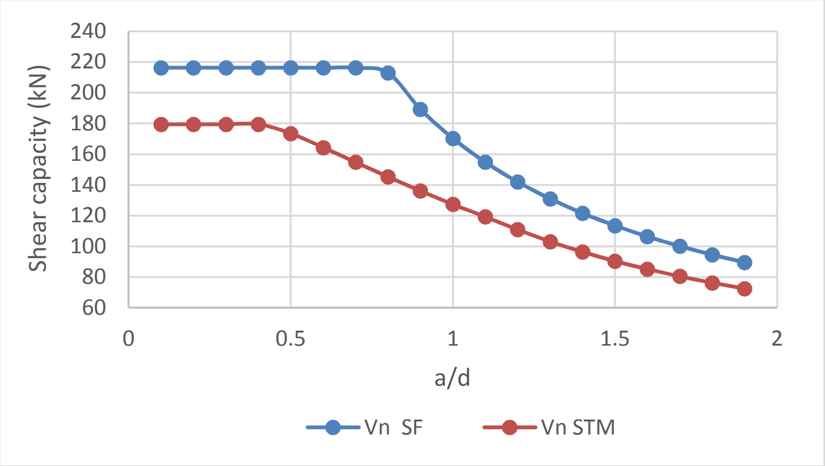


Figure 5: The effect of a/d ratio on the shear capacity of RC corbels

4.1.1. From the results of SF method:

The failure mode for a/d ≤ 0.7 is shear failure with same value because the shear capacity calculated by using shear friction equation is not affected by a/d values. The effect of a/d appears when the failure mode of the specimen is flexural because the moment increases when a/d increases. Therefor SF method is limited for a/d less than unity only. In case of a/d ratio decreases from 0.1 to 1.9, the shear capacity of corbel increases by about 58.5% when using SF and 59.4% when using STM.

4.1.2. From STM method:

The failure mode for a/d ≤ 0.4 is diagonal shear failure with same value because the shear capacity that calculated from maximum nominal shear equation is not affect by a/d values. By increasing a/d value, the failure mode changes to compression strut and the load capacity decreases with increasing a/d. The decrease in shear capacity is 59.43% when a/d value increases from 0.1 to 1.9.

From the comparison between two methods above, it can be concluded that SF method couldn’t give accurate estimation for the corbel strength when a/d > 1. This is attributed to that fact that SF assumes flexural failure mode, while it is compression strut failure by STM assumption.

4.2. Effect of width:

Twenty-one specimens are used to investigate the effect of corbel width on the strength of RC corbels, Table 2 and Figure (6).

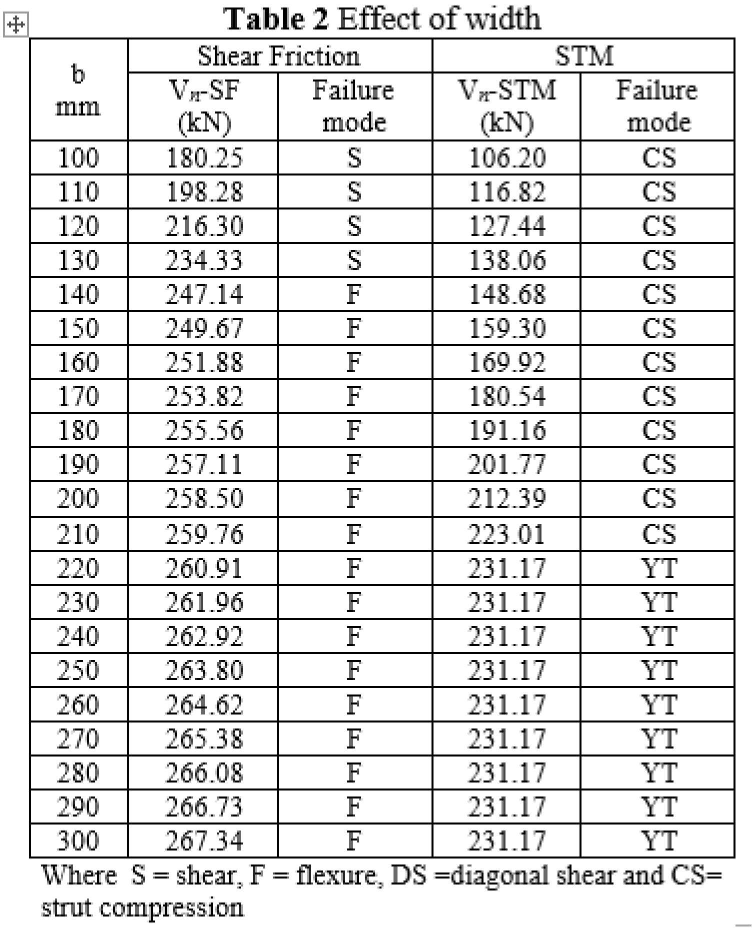


Table 2 Effect of width

b mm	Shear Friction		STM	
	V_n-SF (kN)	Failure mode	V_n-STM (kN)	Failure mode
100	180.25	S	106.20	CS
110	198.28	S	116.82	CS
120	216.30	S	127.44	CS
130	234.33	S	138.06	CS
140	247.14	F	148.68	CS
150	249.67	F	159.30	CS
160	251.88	F	169.92	CS
170	253.82	F	180.54	CS
180	255.56	F	191.16	CS
190	257.11	F	201.77	CS
200	258.50	F	212.39	CS
210	259.76	F	223.01	CS
220	260.91	F	231.17	YT
230	261.96	F	231.17	YT
240	262.92	F	231.17	YT
250	263.80	F	231.17	YT
260	264.62	F	231.17	YT
270	265.38	F	231.17	YT
280	266.08	F	231.17	YT
290	266.73	F	231.17	YT
300	267.34	F	231.17	YT

Where S = shear, F = flexure, DS =diagonal shear and CS= strut compression

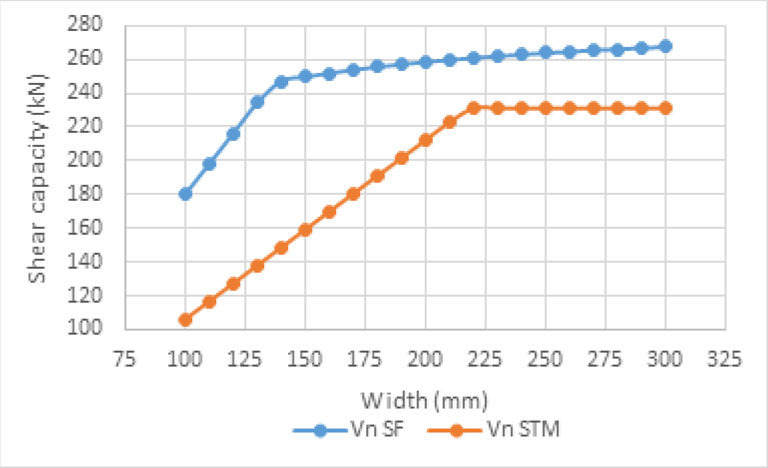


Figure 6 The effect of width

4.2.1. From the result of SF method:

The failure mode is shear for b ≤ 130 mm, but when the width increases, the corbel specimen will be controlled by flexural failure. It is seen that when the width increases from 100 mm to 300 mm, i.e. by about 66.67%, the shear capacity increases by about 32.58%. That takes place because when the width increases, the concrete becomes stronger, which transforms the failure from shear into flexural.

4.2.2. From STM method:

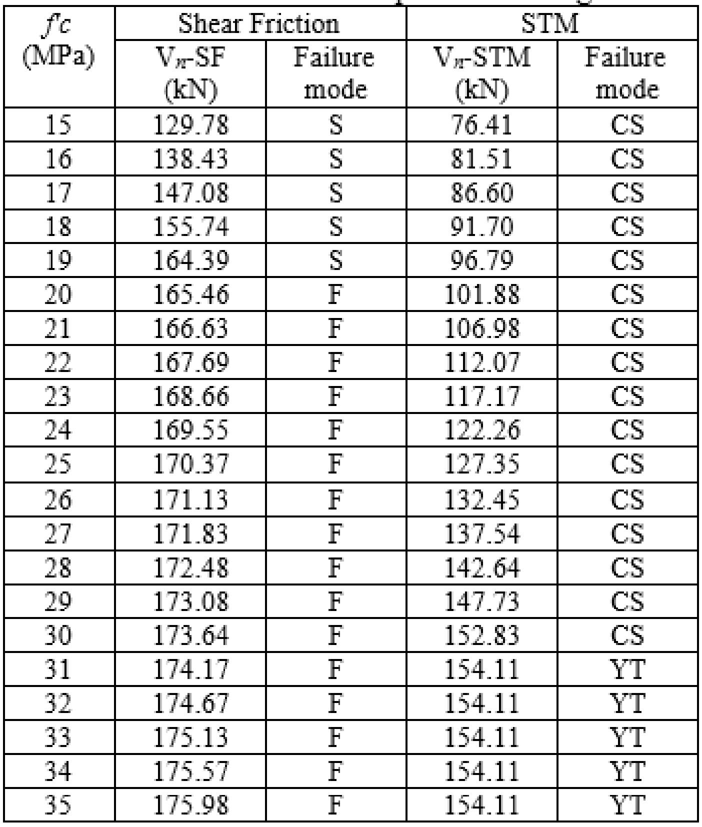
The failure mode is strut compression failure for b ≤ 210 mm, but when the width increases, the corbel fails by yielding of tie reinforcement failure. It is found that when the width increases from 100 mm to 300 mm, i.e. by about 66.67%, the shear capacity increases by about 54%. This happens because when the width increases, the strut increases, so the failure transforms from strut into tie.

It is worth to mention that when the effect of width is studied, main reinforcement had been taken 678.6 mm^2, because the increase in width causes here an increase in section capacity. In other words, by using scarce reinforcement, the failure occurs in reinforcement and the effect of width increasing becomes unclear.

4.3. Effect of compressive strength:

Compressive strength of concrete is considered the most important characteristic because concrete is a distinctive compressive material as shown in Table 3 and Fig. 7.

Table 3 Effect of Compressive strength



f'c (MPa)	Shear Friction		STM	
	V_n-SF (kN)	Failure mode	V_n-STM (kN)	Failure mode
15	129.78	S	76.41	CS
16	138.43	S	81.51	CS
17	147.08	S	86.60	CS
18	155.74	S	91.70	CS
19	164.39	S	96.79	CS
20	165.46	F	101.88	CS
21	166.63	F	106.98	CS
22	167.69	F	112.07	CS
23	168.66	F	117.17	CS
24	169.55	F	122.26	CS
25	170.37	F	127.35	CS
26	171.13	F	132.45	CS
27	171.83	F	137.54	CS
28	172.48	F	142.64	CS
29	173.08	F	147.73	CS
30	173.64	F	152.83	CS
31	174.17	F	154.11	YT
32	174.67	F	154.11	YT
33	175.13	F	154.11	YT
34	175.57	F	154.11	YT
35	175.98	F	154.11	YT

Where S = shear, F = flexure, CS = strut compression and YT= yield of tie

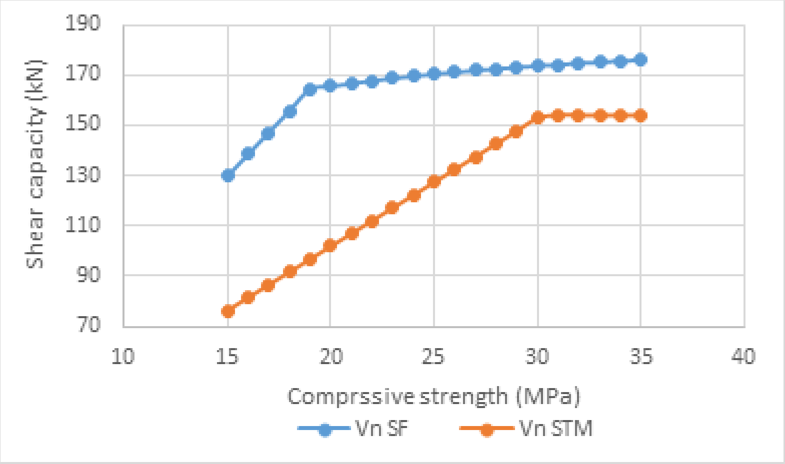


Figure 7 The effect of compressive strength

4.3.1. From the results of SF method:

The failure mode is shear for $f'c \leq 19$ MPa, but when *f'c* increases, the corbel specimen will be controlled by flexural failure. That happens because when *f'c* increases, the failure in compressive strut becomes difficult, so the flexural failure takes place.

4.3.2. From STM method:

The compressive strength is very important parameter because strut is a compression member that is affected mainly by *f'c* value. Therefore, the failure mode is strut compression for *f'c* ≤ 30 MPa, but when *f'c* increases, the corbel specimen will be controlled by tie failure. It was also seen that when *f'c* becomes greater than 30 MPa, normal and high strength concrete corbels have the same behavior. Finally, it is worth to mention that when *f'c* increases from 15 MPa to 35 MPa, i.e. 75.14%, the shear capacity increases by about 50.4%.

4.4. Effect of reinforcement yield strength:

Since tie is a tensile member, it must be reinforced to resist tensile forces. Yield strength of steel reinforcement gives indication about reinforcement resistance to yielding failure as shown in Table 4 and Fig. 8.

Table 4 Effect of reinforcemet yield strength

fy (MPa)	Shear Friction		STM	
	V_n-SF (kN)	Failure mode	V_n-STM (kN)	Failure mode
400	170.27	F	146.80	YT
410	174.26	F	150.47	YT
420	178.23	F	154.14	YT
430	182.18	F	157.81	YT
440	186.13	F	161.48	YT
450	190.05	F	165.15	YT
460	193.97	F	168.82	YT
470	197.87	F	172.49	YT
480	201.76	F	176.16	YT
490	205.64	F	179.83	YT
500	209.50	F	183.50	YT
510	213.35	F	187.17	YT
520	217.19	F	190.84	YT
530	221.01	F	194.51	YT
540	224.82	F	198.18	YT
550	228.62	F	201.85	YT
560	232.40	F	205.52	YT
570	236.17	F	209.19	YT
580	239.92	F	212.39	CS
590	243.67	F	212.39	CS
600	247.39	F	212.39	CS
Where S = shear, F = flexure, CS = strut compression and YT= yield of tie				

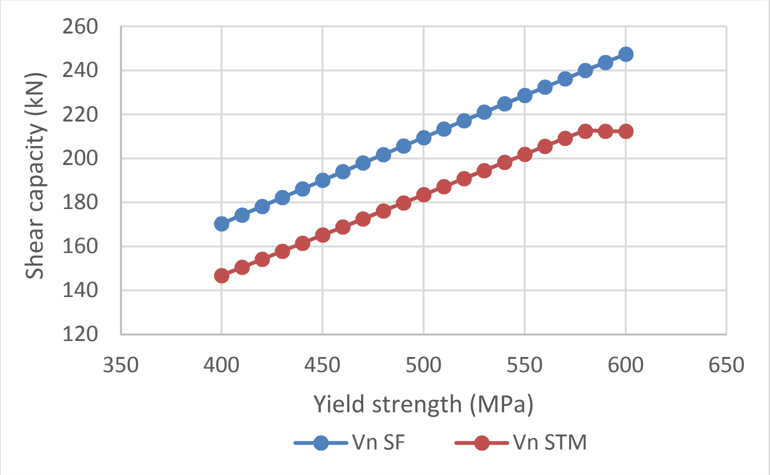


Figure 8 The effect of yield strength

4.4.1. From the results of SF method:

By increasing *fy* value from 400 MPa to 600 MPa, i.e. by 33.3%, the shear capacity increases by about 31.2% in conjunction with flexural failure. This failure mode takes place due to the increase of main reinforcement strength.

4.4.2. From STM method:

The failure mode is reinforcement yielding of tie failure for $fy \leq 570$ MPa, but when *fy* increases, the failure mode becomes compression strut. The increase of *fy* value from 400 MPa to 600 MPa, i.e. 33.3%, leads the shear capacity to increase by about 30.9%. It is worth to say here that the width had been taken 200 mm instead of 120 mm in order to clarify the effect of *fy* in a firmer way.

4.5. Effect of horizontal to vertical load ratio:

The source of horizontal load in corbel is shrinkage, creep and temperature change of supported beam that causes direct tension on corbel main or tie reinforcement. In this study, different values of H/V are considered as shown in Table 5 and Fig. 9.

Table 5 Effect of horizontal to vertical load ratio

H/V	Shear Friction		STM	
	V_n-SF (kN)	Failure mode	V_n-STM (kN)	Failure mode
0	170.37	F	127.44	CS
0.05	162.97	F	127.44	CS
0.1	156.14	F	127.44	CS
0.15	149.81	F	127.44	CS
0.2	143.93	F	127.44	CS
0.25	138.46	F	127.44	CS
0.3	133.37	F	123.95	YT
0.35	128.62	F	120.04	YT
0.4	124.18	F	116.36	YT
0.45	120.02	F	112.91	YT

0.5	116.12	F	109.65	YT
0.55	112.45	F	106.57	YT
0.6	108.99	F	103.67	YT
0.65	105.74	F	100.91	YT
0.7	102.67	F	98.30	YT
0.75	99.76	F	95.82	YT
0.8	97.02	F	93.47	YT
0.85	94.41	F	91.22	YT
0.9	91.90	F	89.08	YT
0.95	89.59	F	87.04	YT
1	87.35	F	85.09	YT
Where S = shear, F = flexure, CS = strut compression and YT= yield of tie				

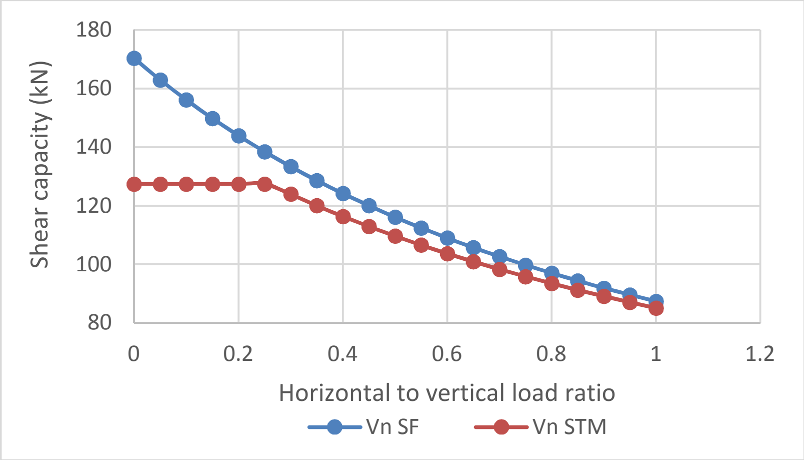


Figure 9 The effect of H/V ratio

4.5.1. From the results of SF method:

The failure mode is flexural in different H/V values. Shear capacity decreases by about 48.7% when H/V increases from 0 to 1. This behavior takes place due to the effect of horizontal load on corbel main reinforcement that reduces the vertical load capacity.

4.5.2. From the results of STM method:

The failure mode is strut compression failure for $H/V \leq 0.25$, which means that there is no effect of horizontal load. Nonetheless, when increasing the H/V value, the failure converts into tie yielding. More specifically, the shear capacity decreases by about 33.2% when H/V increases from 0 to 1. This behavior occurs duo to tensile force effect of horizontal load on corbel tie reinforcement that reduces the vertical shear capacity.

5. COMPARISON BETWEEN SF AND STM IN TERMS OF THEIR RELIABILITY WITH EXPERIMENTAL RESULTS

In order to verify the ratability of SF and STM methods, some experimental data were taken from the literature and compared with the theoretical solutions of the both methods, Table 6.

Table 6: Verification of SF and STM with experimental results

Author	Specimens	V_n-test (kN)	V_n-SF (kN)	V_n-STM (kN)	V_n-test/ V_n-SF	V_n-test/ V_n-STM
Mattock et al. [7]	A2	158.3	175	130	0.9	1.22
	A3	124.5	183.35	103.83	0.68	1.2
	B1	209.15	173	117.73	1.2	1.77
	B2	173	164.67	134.84	1.05	1.28
	B3A	187.3	193.59	117.79	0.97	1.59
Yong and Balaguru [13]	C1	796.2	470.4	370.37	1.692	2.15
	C2	836.2	470.4	370.37	1.777	2.25
	D1	700.6	497	430.66	1.41	1.627
	D2	800.6	497	430.66	1.611	1.859
Foster et al. [14]	SC1-1	720	412.5	590.56	1.745	1.219
	SC1-2	950	412.5	590.56	2.303	1.609
	SC1-3	700	412.5	418.58	1.697	1.672
	SC1-4	470	412.5	386.59	1.139	1.216
	SC2-1	980	412.5	490.16	2.376	1.999
	SC2-2	700	412.5	490.16	1.697	1.428
	SC2-3	580	412.5	386.6	1.406	1.500
	SC2-4	490	412.5	386.6	1.188	1.267
Wilson et al. [15]	C0	1426.2	1093.4	1105	1.304	1.29
	C1	1677.65	1093.4	1105	1.632	1.615
	C2	1784.45	1093.4	1105	1.632	1.615
	C3	1544.15	1093.4	1105	1.412	1.397

where S=shear, F = flexural, DS =diagonal shear and YT= yield of tie

From the above comparison shown in Table 6, SF method is more reliable than STM in relation with Mattock et al. [7] experimental results. That can be attributed to the fact that Mattock et al. relied on shear strength on the one hand, and on the other hand, relied on normal strength concrete in which the maximum average shear stress 5.5MPa is not involved.

The other comparisons [13, 14, 15, 16, 17] show that STM is more reliable than SF because

1-The failure types that are defined by STM are more reliable because they contain diagonal crush, diagonal splitting or tie, i.e. not only shear friction or flexural like in SF method.

2-SF method can be used when a/d<1, otherwise, the corbel becomes cantilever. Whereas, STM deals with the corbel till a/d<2, because it becomes here deep corbel.

3-SF does not give accurate results when the high strength concrete is used. That is because the maximum average shear stress is limited to 5.5MPa or 0.2f'c, which is minimum. In other words, when f'c>27.5MPa, f'c value does not affect the results of SF.

4-The factor of safety in STM is more than that in SF that is why. STM is more favorable for the engineers.

6. CONCLUSIONS

1. Comparing with the experimental data, the shear capacity calculated by SF method is greater than that calculated by STM method.
2. The shear capacity of corbel increases by about 58.54% for SF and 59.43% STM when the a/d ratio decreases by about (0.1-1.9) %.
3. The effect of a/d in SF method appears when the specimens fail by flexure because the moment increases when a/d increases. In STM method, a/d value is considered very effective on shear capacity.
4. The increase of corbel width by about (100-300) % leads to increase shear capacity by about 32.58% for SF and 54.06% for STM.
5. The increase of concrete compressive strength of corbel by about (15-35) % leads to increase load capacity by about 26.25% for SF and 50.42% for STM.
6. The behavior of normal and high strength concrete corbel is the same because the corbel may fail by tension of main reinforcement or tension stress on strut itself.
7. The load capacity of corbel increases by about 31.17% for SF and 30.88% for STM when the yield strength of the main reinforcement increases by about (400-600) %.
8. The presence of horizontal force in corbel leads to decrease vertical load capacity.
9. The failure mode in STM method is more accurate and virtual than SF method because it take in consideration strut and diagonal shear failure mode, which is very popular in RC corbel.

LIST OF NOTATIONS

A_s	Total area of the primary reinforcement
A_h	total area of the secondary reinforcement
A_{vf}	Total area of shear friction reinforcement
a	Shear span, mm
b	Width of the corbel, mm
d	Effective depth of the primary reinforcement at the face of the column, mm
$f'c$	compressive strength of the concrete), MPa
f_{ct}	Indirect tensile strength (splitting tensile strength), MPa
fy	yield strength of the primary reinforcement), MPa
h	Total depth of deep beam, mm
L_s	Length of support bearing block, mm
L_b	Length of load bearing block, mm
M_n	Nominal moment capacity at the column face
V_n	Nominal shear strength of the corbels, equal to half of the nominal load-carrying capacity of the specimens, kN
w_s	Width of horizontal strut, mm
w_t	Width of anchor tie, mm
w_{eff}	Effective width of strut, mm
w_{sb}	width of inclined strut at support
w_{st}	width of inclined strut at load
βs	Strut coefficient according to Table 23.4.3 in ACI 318-14 provisions
θ	Angle between the inclined strut and the tie
α	Angle of inclination of reinforcement to the axis of the beam
μ	Coefficient of friction used in shear-friction calculations according to Table 22.9.4.2 in ACI 318-14 provisions

λ Modification factor reflecting the reduced mechanical properties of lightweight concrete

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