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BEHAVIOR OF HIGH STRENGTH CONCRETE SHALLOW BEAMS IN SHAEAR

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ملخص البحث:
برغم إهتمام العديد من الجهات البحثية بالخرسانة عالية المقاومة إلا أن المجال يتطور يوم بعد يوم و إستخدام الخرسانة عالية المقاومة يزداد شيوعا ولهذا تم عمل برنامج بحثي وضع لدراسة صلاحية معادلات الأكواد الحالية للكمرات الضحلة المصبوبة بأستخدام خرسانة عالية المقاومة و دراسة تأثير نسبة تسليح القص و مسافات الكانات و قطر الكانات المستخدمة.
ستة كمرات ضحلة تم صبها بأستخدام خرسانة عالية المقاومة (ذات مقاومة مميزة 67.4 نيوتن/مم2) بأبعاد (400 مم عرض و 200 مم سمك و 1800 مم طول بحر) صممت لكي تنهار فقط تحت إجهادات القص مع دراسة المتغيرات التالية : إختلاف نسب التسليح المقاوم للقص, مسافات الكانات و قطرالكانات هذا و واحدة من العينات تم صبها بدون كانات كعينة مرجعية و لتوضيح تأثير التسليح الطولي (المقاوم للإنحناء) على مقاومة القطاع في القص و تهدف الورقة البحثية لدراسة سلوك الكمرات الخرسانية الضحلة المصبوبة بأستخدام خرسانة عالية للمقاومة مع الأخذ في الإعتبار تاثير زيادة حديد القص و المسافات بين الكانات و قطر الكانات المستخدمة و مقارنة القيم الفعلية بقيم الأكواد المختلفة مع تقديم تعديل مقترح على معادلة الكود المصري لحساب مقاومة القص للكمرات الضلحة.

ABSTRACT:
Although many international standards give attention to High strength concrete. But the field is updating, new ranges of concrete strength reached every day and the usage of high strength concrete becoming very common day after day; experimental program was conducted to study the applicability of current standard equations on the shallow high strength concrete beams with respect to shear reinforcement percentage, spacing of stirrups and diameter of shear reinforcement used.
Totally 6 full scale shallow beams were casted using high strength concrete (Fcu= 67.4Mpa) with dimensions (1800X400X200) designed to insure shear failure with different shear reinforcement ratios, stirrups spacing and stirrups diameter; one of the samples was casted without shear reinforcement as a control sample and to study the effect of Flexure reinforcement on shear strength. This paper investigates the behavior of shallow beams casted using high strength concrete with respect to variation in reinforcement ratio, stirrups spacing, and diameter of the stirrups and to study the actual shear capacity of the beams without Shear reinforcement. And proposed modification to ECP equation of shear strength

Keywords: Shear strength, Shallow beams, Stirrups diameter, High strength concrete HSC, Stirrups spacing.

1. INTRODUCTION:
In Modern buildings, many architectural constraints forcing the designers to provide longer spans and less protruding beams at a reasonable cost. Which can be achieved through the use of either shallow Hidden beams or flat plate slabs systems.

According to Egyptian Code of practice (ECP 203-2007) [1] the shear stress in shallow wide beams must be less than the concrete shear strength without any contribution of shear reinforcement. Also the code limit the shear strength provided by concrete for shallow beams to 67% of the concrete shear strength of the regular dropped beams. And force the use of min shear reinforcement. Which leads to a larger portion of concrete slab to be reinforced as a hidden beam and with high values of flexure reinforcement concrete to meet beam requirements. Which leads to a very conservative design. Also for the Shear design of hidden wide beams, the code requires the stirrups to be arranged so that the distance between branches of stirrups not to exceed 250 mm.

High-strength concrete has gained an increased interest in reinforced concrete structures in last decades as it generally leads to the design of smaller sections. and reduces the own weight, which allow longer spans and smaller mass (smaller seismic effect).,duo to the usage of high strength mortar close to the strength of the aggregate the shear strength of High strength Concrete was always a questionable since the concrete shear strength depend partially on the aggregate interlock .Also the definition of High strength concrete is vague For example in the 1950s, concrete with compressive strength ($f_c^{'}$) of 35 N/mm^2 was considered to be high strength concrete. Currently, In the Iconic tower In Central business district in the new administrative capital of Egypt the concrete used in the tower core wall (f_{cu}) equal 85 N/mm^2. According to “High-Strength Concrete: A Practical Guide” by Michael A. Caldarone [6] HSC is the concrete made with normal weight aggregate with a compressive strength higher than 50 MPa; There is a very few researches focused on the shear in Hidden beams specially the one cased with High strength concrete the following section summarize some of the previously exerted effort in this subject.

“On the Contribution of Shear Reinforcement in Shear Strength of Shallow Wide Beams” by Mohamed M. Hanafy, Hatem M. Mohamed and Nabil A.B. Yehia Life Science Journal 2012;9 [3] carried out an experimental study to investigate the shear behavior of hidden beams (wide shallow beams) the experimental program included twelve simply-supported reinforced

Concrete wide beams subjected to two concentrated loads at third points. The specimens were divided into 5 groups. All specimens were typically proportioned so that shear failure would preclude flexural failure. Shear strengths at failure recorded in this experimental program are compared to the analytical strengths calculated according to some international codes. Test results clearly demonstrate the significance of the web reinforcement in improving the shear capacity the ductility of the shallow wide beams which is consistent with the recognized international codes and standards provisions the results concluded the following.

1. H.S.C shallow wide beams without web reinforcement presented a more ductile behavior compared to N.S.C beams. On the other hand, H.S.C beams with stirrups, twice as much as the minimum web reinforcement, exhibited a less ductile behavior.
2. For shallow wide beams without web reinforcement the shear strength generally increases as the concrete compressive strength increased.
3. The effect of web reinforcement on improving shear strength is more pronounced at lower compressive strength of concrete and lower reinforcement ratio.
4. The influence of stirrups amount on shear strength does not vary according to concrete compressive strength.
5. The spacing between vertical stirrups and branches number of stirrups in cross section have a less effect in improving shear capacity as concrete strength increases.

6. The shear reinforcement significantly enhances reinforcement; the shear strength generally increases as the concrete compressive strength the ductility of the shallow wide beams with normal strength concrete. This effect is less pronounced with high strength concrete.
"Shear Behavior of Self-Compacting High Strength Concrete I-beams" (Omer A. EL-Nawawy, Ahmed H. Ghallab, and Mohamed A. El-Alfy, 2013)Al-Azhar Magazine[4]

Experimental program of eight I-Sec Beams casted with High strength SCC
The main variables were:

(a) Amount of Shear Reinforcement

(b) Shear span to depth ration (a/d)

(c) Web width of Concrete I-beam

Conclusion:
1- Increasing the shearing span to depth ratio (a/d) decreased the shear capacity of the Concrete beams without web reinforcement and increased the brittle behave.

2- All studied design codes; ACI [318- 2008], ECP [203-2007] and BS [8110-97] were conservative in calculating the shear capacity of high strength self-compacting concrete beams.
3- High strength SCC I-Section beams without web reinforcement showed an extremely brittle behavior when failing in shear.

2. CODES' REVIEW FOR SHEAR OF SHALLOW WIDE BEAMS

Egyptian Code of practice (ECP 203-2007) [1]

The current Egyptian Code of practice (ECP 203-2007) determines the shear resistance of shallow wide beams as following:

$$q_u \leq q_{cu} \quad (1)$$

$$\boldsymbol{q_{cu}} = 0.16\ (f_{cu} / \square_c)^{\wedge 0.5} * b_w * d \quad (2)$$

Where q_{cu} is the concrete shear capacity (N/mm^2), f_{cu} is the concrete cube strength (N/mm^2), $\square_c$ is concrete strength reduction factor =1.50, d is the effective depth of the section (mm).and b_w is the width of the beam (mm). The code neglects the web reinforcement contribution in shear strength of shallow beams, while insist in provide a minimum web reinforcement.

American Concrete Institute (ACI 318-14) [3]

V_n nominal shear strength, = V_c concrete contribution + V_s. shear reinforcement contribution;

$$\square V_n \geq V_u \quad (3)$$

$$V_n = V_c + V_s \quad (4)$$

Where V_u is the ultimate shear force at section, the concrete contribution term,□□ strength reduction factor =0.75 in shear

V_c , can be calculated by either simple equation (5) or the least of equations(6),(7) and (8):

$$V_c = 0.17\ (f_c')^{\wedge 0.5} * b_w * d \quad (5)$$

$$V_c = [0.16\ (f_c')^{\wedge 0.5} + 17\ \rho_w * (V_u * d/M_u)] * b_w * d \quad (6)$$

$$V_c = [0.16\ (f_c')^{\wedge 0.5} + 17\ \rho_w] * b_w * d \quad (7)$$

$V_c = 0.29\,(f_c')^{0.5} * b_w * d$ (8)

If $V_u > \phi V_c$, shear reinforcement must be provided to sustain extra shear:

$V_s = A_v * f_y * d / S \le 0.66(f'_c)^{0.5} * b_w * d$ (9)

Where: V_u = factored ultimate shear force at the section(N), V_c = nominal shear strength provided by concrete (N), V_s = nominal shear strength provided by shear reinforcement (N), V_n = nominal shear strength (N), M_u = factored flexural moment at section (N.mm), ϕ = strength reduction factor = 0.75, $\rho_w = A_s/b_w d$, As = area of longitudinal reinforcement (mm^2), A_v = area of shear reinforcement (mm^2), b_w= web width of section (mm), d= distance from top of section to the longitudinal reinforcement (mm), s = spacing of the transverse reinforcement (mm), f_c'= concrete compressive cylinder strength (MPa), f_y = yield strength of stirrups reinforcement (MPa).

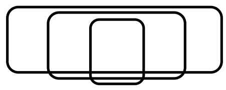
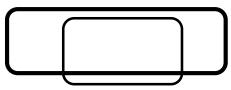
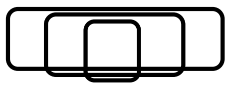
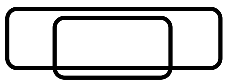
3. EXPERIMENTAL WORK:

The experimental program was carried out to test six simply-supported reinforced concrete beams, the six beams are casted using high strength concrete with compressive strength of f_{cu} =67.4 N/mm^2, Detailed description of the specimens, the material properties, test set-up, equipment, test procedure, and measurements are presented in the below section.

Test Specimens:

In the experimental program, tests were carried out on six concrete beams named (NCC1 to NCC6) where "NCC" refers to normal compaction high strength concrete; The width/depth ratio was 2.42 in all specimens. All specimen were 400mm x 200mm in cross-section with 1800 mm length 1600mm clear span and the same flexure reinforcement (6T16+6T20 Bottom and 6T12 Top). The beams were simply supported and subjected four point loading the details of the tested beams are shown in Table (1) and Fig.1

Table.1 Specimens reinforcement details.

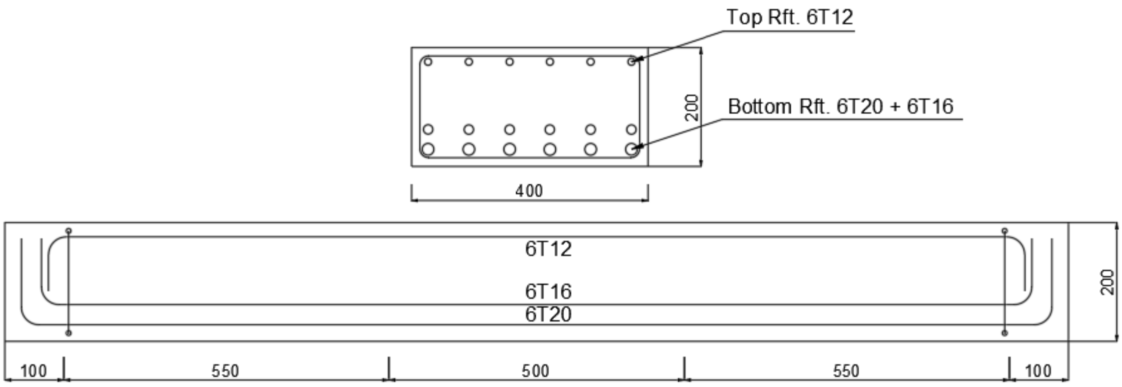
Specimen	Longitudinal RFT		Web Shear RFT.	
	Bottom	Top	Stirrups	Stirrups configuration
NCC1	6T20 + 6T16	6T12	---	---
NCC2			6Y6@200	
NCC3			2Y8+2Y6@200	
NCC4			4Y6@135	
NCC5			6YT8@200	
NCC6			4T8@135	

The test specimens were divided into 4 groups.

Group No. (1): This group consists of four specimens (NCC2) Vs (NCC4) and (NCC5) Vs (NCC6) to study the effect of stirrups spacing and number of branches.

Groups No. (2): This group consists of four specimens (NCC2) Vs (NCC5) and (NCC4) Vs (NCC6) to study the effect of variation in shear reinforcement ratio.

Figure.1 Flexure Reinforcement Configuration of All beams



Groups No. (3): This group consists of two specimens (NCC1) Vs (NCC2) to study the effect of absence shear reinforcement.

Groups No. (4): This group consists of two specimens (NCC2) Vs (NCC3) to study the effect of variation in shear reinforcement diameter.

Materials:

Six Trial mixes were tried in the Concrete Research Laboratory at Cairo University to reach the target cubic compressive strength Fcu = 65 N/mm^2 The Final used mix tried at 28 days from the batch used in casting the actual samples the acquired Avg. Fcu = 67.4 N/mm^2 Table (2) shows mix Design by weight of the quantities needed for one cubic meter of concrete as one used in the experiment

Table.2 Mix Design of High Strength Concrete

Fcu Target (N/mm^2)	Fcu Actual (N/mm^2)	Cement Kg(KN)	Silica Fume Kg(KN)	Crushed Dolomite Kg(KN)	Sand Kg (KN)	Water (liter)	Super-plasticizer (liter)
65	67.4	400(3.92)	0	1080(10.59)	640(6.28)	200	10.5

Test Procedure:

Static load hydraulic loading jack with an electrical load cell was used to apply the vertical load. A digital load indicator with 1 KN accuracy was used to measure the applied load.

Each specimen was centered on the loading machine. Loads were applied of specimens with load increment of 0.5 ton. Figure.3 shows a photograph for the General test arrangement, and Figure.2 shows a schematic view of the test setup. At every load increment, the cracks were observed and marked and continuous recording for deflection and steel strain in longitudinal reinforcement and stirrups, and load value from the loading cell using data accusation system. Failure was considered to occur when the load could not be increased further.

The deflections were measured at the mid-span and under loads of the beam by a dial gauge of 0.01mm accuracy (LVDT instrument). The crack propagation was monitored and drown on the beams during loading. The strain in reinforcement were measured using 100 mm gauge length for one deformed bar in the constant moment region and outer stirrups. All test records were automatically saved on computer file for further data refining and plotting

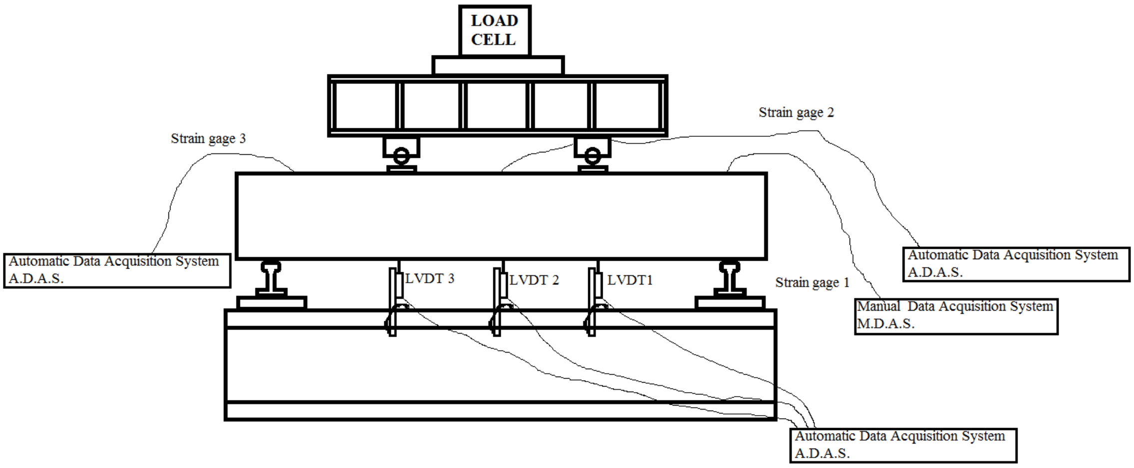


Figure.2, Schematic Test Setup

Figure.3 Test Arrangement

4. TEST RESULT:

Experimental test results of the six specimens includes cracking propagation and final pattern, load - deflection, and load - stirrups strains for each test specimen.

A comparison between test results of the failure load and the ECP 203-2007 [1], ACI 318-14 [2], Values is also presented in this section.

Cracking Pattern and Mode of Failure:

In General all specimens, the first crack appear was a Flexure crack thin after a while the shear cracks starts to propagate and the flexure crack reach static case. The shear crack starts to develop a full diagonal crack thin the beam resist until fail in shear. The recorded values were

First Binding Crack load, First shear crack load, load at First Full diagonal Crack and Failure load.

Table 3 summarizes the results of the Sex tested beam specimens. The table gives the recorded loads at different loading stages for each specimen. (1 Ton = 9.81 KN)

Table.3 Summary of experimental results.

Sample Name	First Binding Crack (Ton)	First Shear Crack (Ton)	First Diagonal Crack (Ton)	Failure load (Ton)	Max Shear Force (Ton)	Max. deflection (mm)	stirrups configuration
NCC1	10	20	35	55	27.5	8.75	---
NCC2	15	25	40	57.4	28.7	10.5	6Y6@200
NCC3	15	30	40	60	30	7.25	2Y8+2Y6@200
NCC4	15	35	40	55	27.5	9.0	4Y6@135
NCC5	20	30	35	65	32.5	9.25	6YT8@200
NCC6	10	20	35	60.5	30.25	9.25	4T8@135

PS. Cracking load values rounded to the nearest 0.25 ton

Figures.4 showing the experimental results, failure & cracking patterns for all specimens.

Figure.4a, Crack pattern for Specimen NCC1.

Figure.4b, Crack pattern for Specimen NCC2.

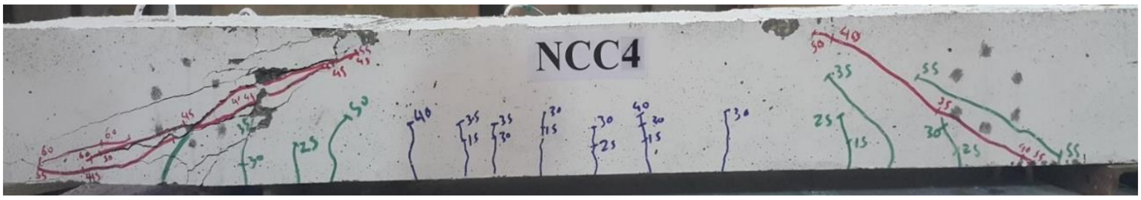


Figure.4c, Crack pattern for Specimen NCC3

Figure.4d, Crack pattern for Specimen NCC4.

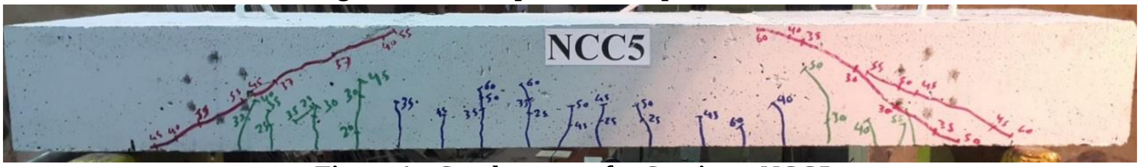


Figure.4e, Crack pattern for Specimen NCC5.

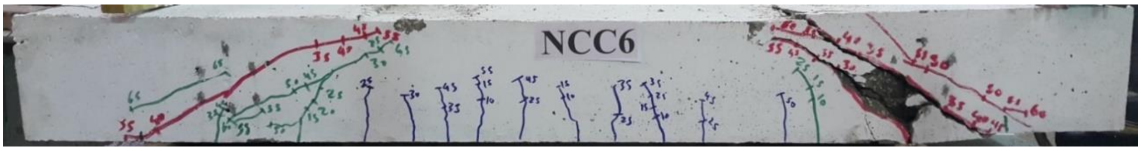


Figure.4f, Crack pattern for Specimen NCC6.

Load-Deflection Relationship:

For each beam the deflection was measured at mid span and as previously shown in the test set up. Values recoded using data accusation system during loading and until failure the deflection values used for comparison purpose between beams. Generally, three stages were observed;

- The linear stage; the curves shows linear behavior associated with un-cracked sections. All curves were almost linear up to the cracking load and extend of this stage is function of the tensile strength of concrete.
- The semi-linear stage; the curves shows almost linear behavior associated with cracked propagation and widening curves were almost linear up to the ultimate load.
- The non-linear stage; the curves shows nonlinear behavior associated with failure crack widening. Curves fluctuate till failure.

Figure.5 shows the load verses deflection curves for each beam Table 4 summarize Deflection values cross ponding to each stage:

Table.4 Summary of recorded deflection values

Specimen	Δ Binding cracking (mm)	Δ Shear cracking (mm)	Δ Diagonal crack (mm)	Δ failure (mm)
NCC1	2.25	3.25	5.0	8.75
NCC2	2.5	3.75	6.25	10.5
NCC3	1.75	2.75	4.5	7.25
NCC4	2.5	4.5	6	9.0
NCC5	2.25	3.75	4.25	9.25
NCC6	2.25	3.5	4.5	9.25

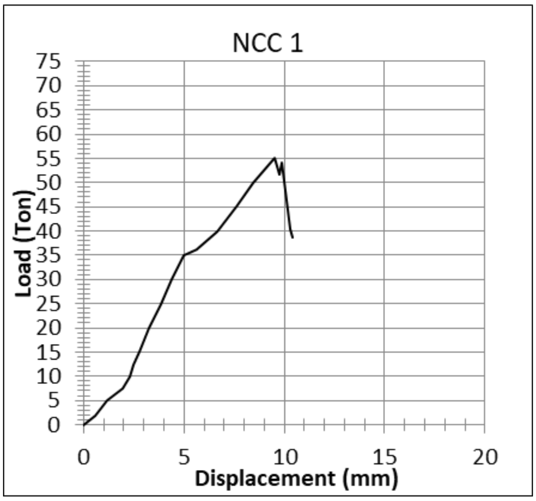


Figure.5a Load-Deflection Beam NCC1

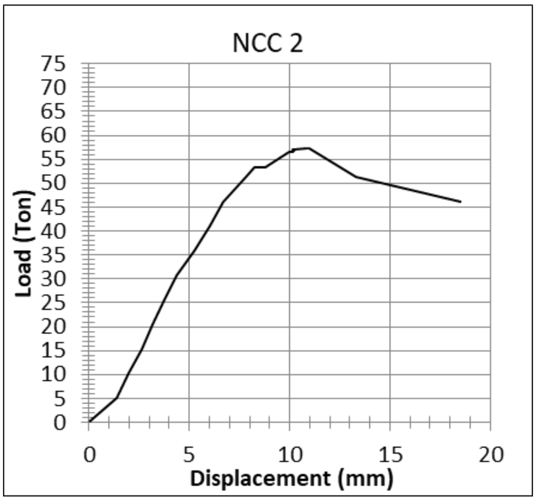


Figure.5b Load-Deflection Beam NCC2

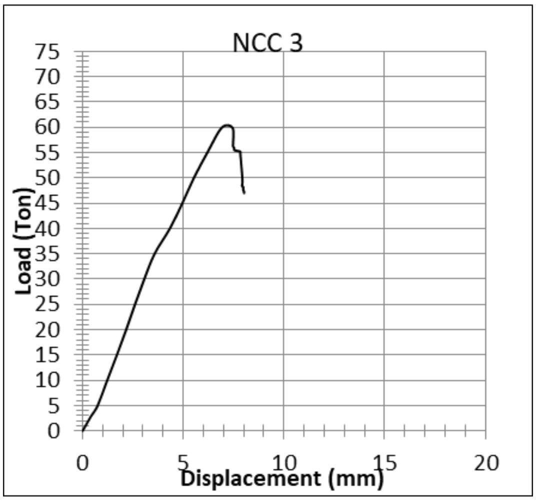


Figure.5c Load-Deflection Beam NCC3

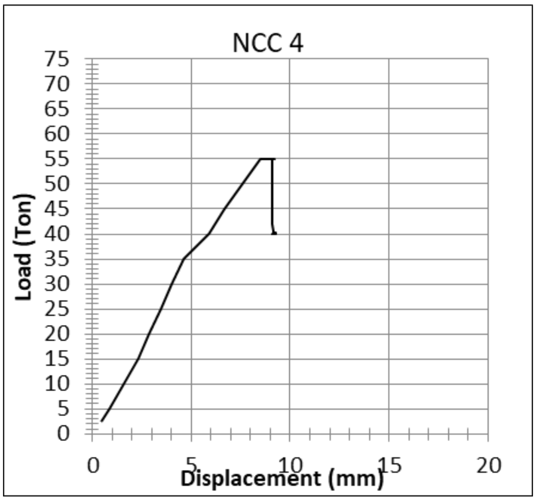


Figure.5d Load-Deflection Beam NCC4

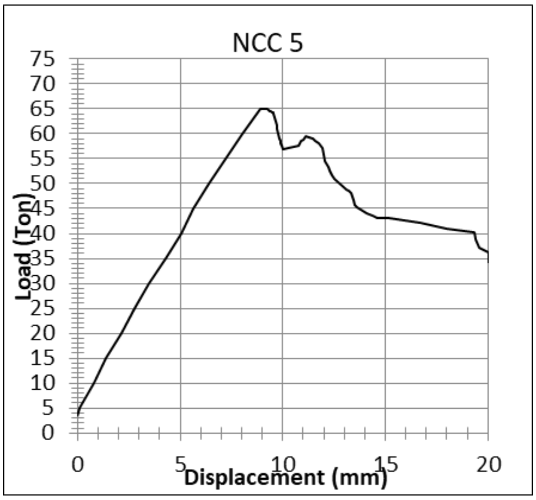


Figure.5e Load-Deflection Beam NCC5

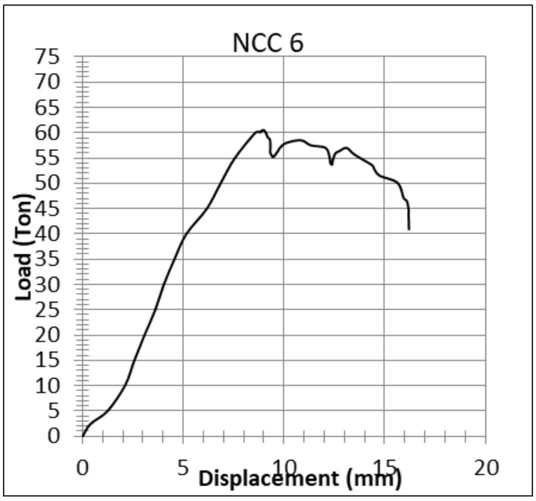


Figure.5f Load-Deflection Beam NCC6

5. DISCUSSION OF RESULTS

Effect of variation in shear Reinforcement spacing and number of branches on beam strength and behavior:

For the shallow wide beam it is important to study the significant of number of branches and spacing because they are typically wider and require larger number of branches the group of beams study this point consist of four beams forming two pairs of beams each pair consist of two beams with the same reinforcement ratio, stirrups diameter, concrete grade, concrete workability and flexure reinforcement they only differ in number of branches and spacing. Table.5 illustrate each pair and the difference in stirrups branches and spacing

Table.5 First study group (effect of spacing and number of Branches).

Pair1					
NCC2	3T6@200	Ult. Load=57.4	NCC4	2T6@135	Ult. Load=55.0
Pair 2					
NCC5	3T8@200	Ult. Load=65.0	NCC6	2T8@135	Ult. Load=60.5

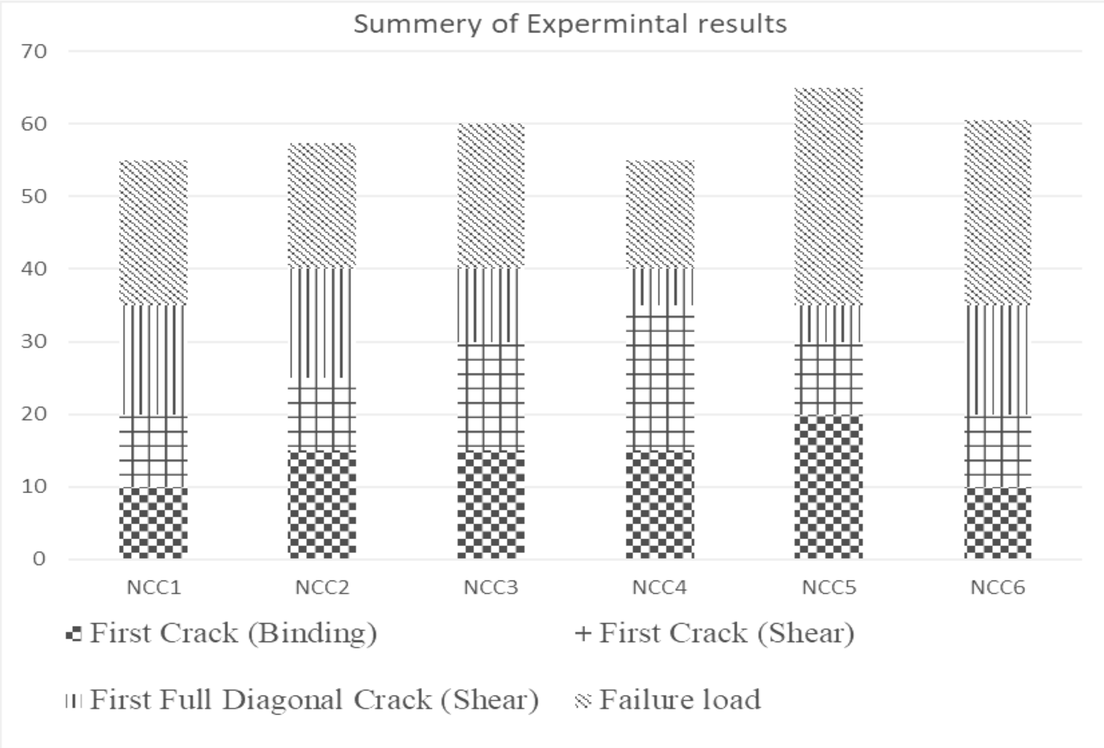


Figure.6 Summery of experimental results

As seen from Figure.6 and Table.4 we notice a small decrease by about 6 % in beam ultimate strength when decreasing Number of branches and decreasing the spacing. For the max deflection recoded value which indicate the ductility (area under P-Δ) we notice either steady or small reduction by about 10%.

Effect of variance in reinforcement ratio on beam strength and behavior:

to study the effect of variance in shear reinforcement we formed a group of two pairs each pair consist of two beams with the same stirrups spacing, number of branches, concrete grade, concrete workability and flexure reinforcement they only differ in reinforcement ratio and shear reinforcement par diameter the contribution of increasing reinforcement par diameter is negligible as shown in the next article.

Table.6 second study group (effect of variation in shear reinforcement)

Pair 1					
NCC2	3T6@200	Ult. Load=57.4	NCC5	3T8@200	Ult. Load=65.0
Pair 2					
NCC4	2T6@135	Ult. Load=55.0	NCC6	2T8@135	Ult. Load=60.5

As seen from Figure.6 and Table.4 we notice positive correlation between reinforcement ratio and ultimate strength in both pairs the strength increased by about 12% when shear reinforcement ratio increased. For the max deflection recoded value which indicate the ductility (area under P-Δ) there is no clear relation the values up and down by about10%. Which indicate that increasing shear reinforcement after a certain limit has no effect on beam ductility.

Effect of shear reinforcement diameter on beam strength and behavior:

Last parameter in this study the effect of stirrups diameter in the beam strength and behavior. The group of beams study this point consist of two beams with the same reinforcement ratio, same stirrups spacing, concrete grade, concrete workability and flexure reinforcement they only differ in diameter of outer stirrup and number of branches which shows about 6% increase in beam ultimate strength Table.7 illustrate each pair and the difference in stirrups branches and spacing

Table.7 Third study group (effect of shear reinforcement diameter).

Pair 1					
NCC2	3T6@200	Ult. Load=57.4	NCC3	1T6+1T8@200	Ult. Load=60.0

We notice about the same 6 % increase in beam strength in NCC3 than NCC2 which also increasing the outer stirrups diameter has a counter effect to the reduction in stirrups branches, so we can assume that the increase in outer stirrups diameter increase the beam strength by about 10%

Comparison between test results and code prediction for shear strength

From results of NCC1 without any shear reinforcement According to the ECP the beam shear strength shall be equal:

Q_{cu} = 0.16 (f_{cu} / γc)^0.5* b_w* d = 0.16*(67.4/1)^0.5*400*165= 86.7 KN = 8.84 Ton

The ECP multiply loads by factor 1.4 D &1.6 Live let's assume average value = 1.45

The expected experimental load according to ECP = 8.84*1.45 = 12.8 ton

From results of NCC1 without any shear reinforcement According to the ACI the beam shear strength shall be equal:

V_u = 0.17 (f'_c)^0.5* b_w* d = 0.17*(67.4*0.8)^0.5*400*165=82.4 KN =8.4 Ton

The ACI multiply loads by factor 1.4 D &1.2 Live let's assume value = 1.4

The expected experimental load according to ACI = 8.4*1.4 = 11.76 ton

A seen in Figure.7 the codes underestimate the shallow beams strength

Both ACI and ECP shear strength value are less than half the experimental value

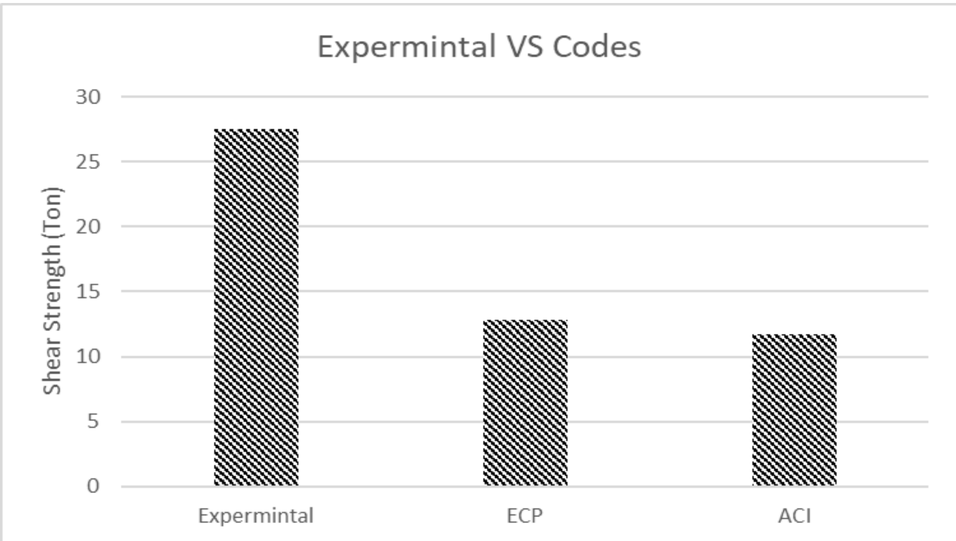


Figure.7 Experimental VS Code limits.

6. CONCLUSION:

Based on the experimental results and the observed behavior, the following conclusions may be made:

- Both ECP and ACI underestimate the hidden beams strength that we may propose to multiply the equation by magnification factor equal 2.0.
- The ECP recommendation to sustain shear force in Hidden beams by only concrete is more realistic since the contraption of shear reinforcement was from 5% to 18% at maxim cases which can be considered as a factor of safety impede in code equation in case we added the earlier proposed magnification factor.
- The larger the number of branches the better performance of beam in strength and ductility by about 6%.
- Spacing has a negligible effect in shallow beams probably because the shallow section the crack will only path throw one row.
- Increase of outer stirrups diameter enhanced the Beam strength by about 10%.

References:

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